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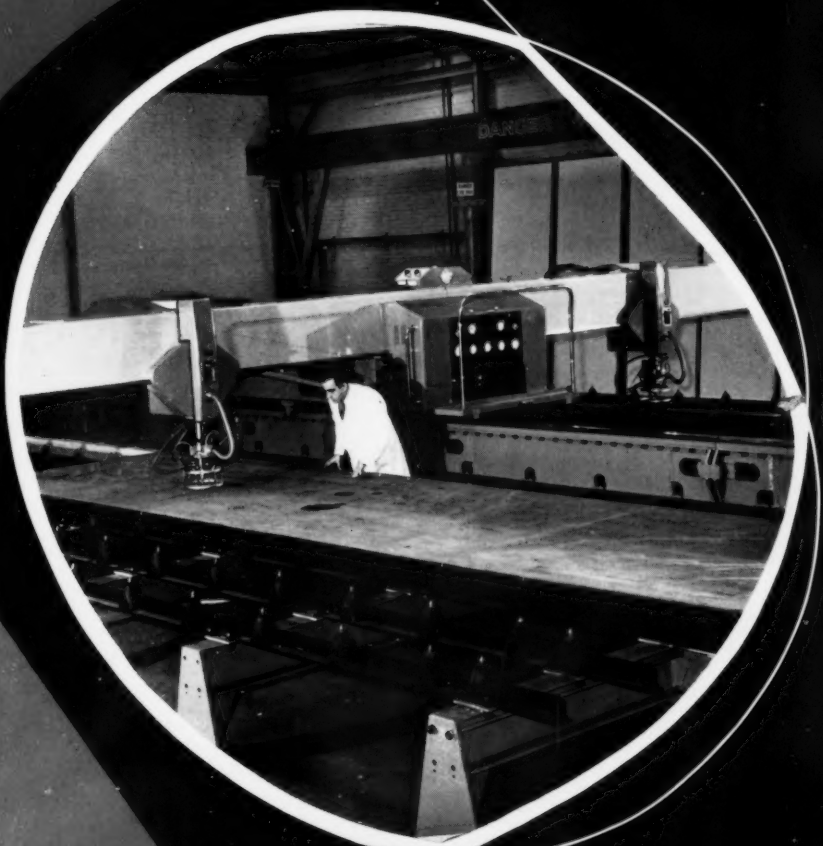

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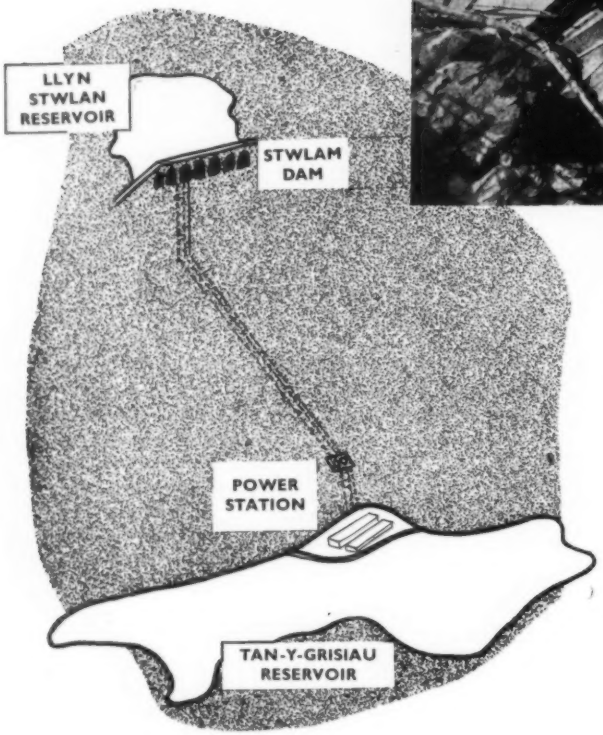
21 films per joint are used on a single exposure technique covering all circumferential welds on site.



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X-Ray Film for examining the circumferential butts on the thousands of feet of weld involved, on pipelines ranging between 6'-10" and 9'-6" diameter used at Ffestiniog, had to be chosen carefully, too. INSPECTION SERVICES LTD. of SUTTON, SURREY, cover the circumferential butt welds by 100% check, with spot checks of longitudinal butts, and throughout they are using Kodak Industrial X-Ray film.

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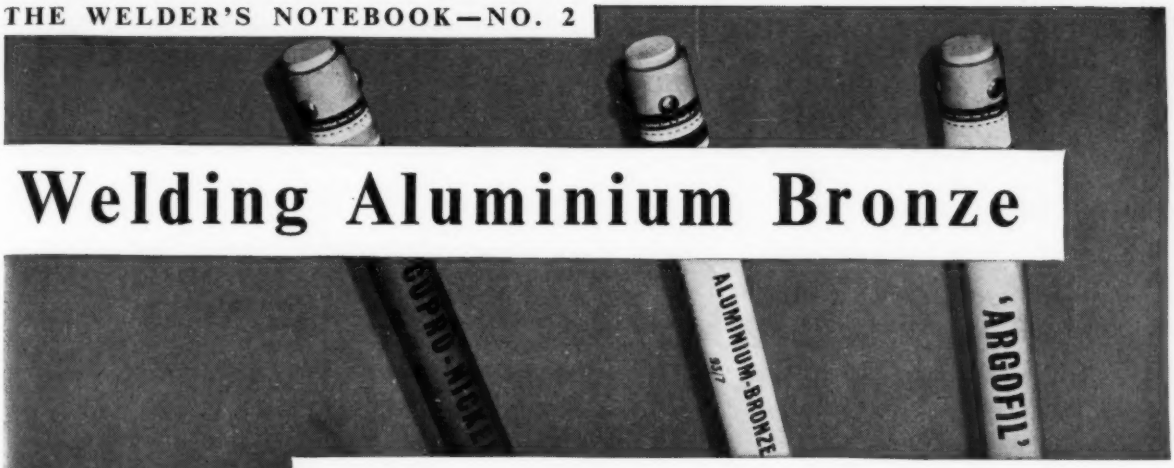

Welding Aluminium Bronze

Aluminium bronze alloys are being used increasingly in chemical and marine engineering, because of their strength and corrosion resistance. Fortunately, advances in welding techniques have eased the problems previously met in joining these useful metals. With the development of improved electrodes, the metal-arc process has been successfully practised for many years. The introduction of shielded-arc techniques has since eliminated problems of oxide and slag removal. To avoid stoppages due to arc burn-back, filler wires must be absolutely free from surface oxide films and grease. All aluminium bronze fillers made by I C I Metals Division are specially treated to provide a chemically clean surface.

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Aluminium bronze Alloy D.	$\frac{1}{16}$ in. and $\frac{1}{8}$ in. diameter in straight lengths. Also on spools for I.G.S.M.A. welding	Argon arc and I.G.S.M.A.	1060-1080
Aluminium bronze Alloy E.	On spools for I.G.S.M.A. welding	I.G.S.M.A. only	1035-1055

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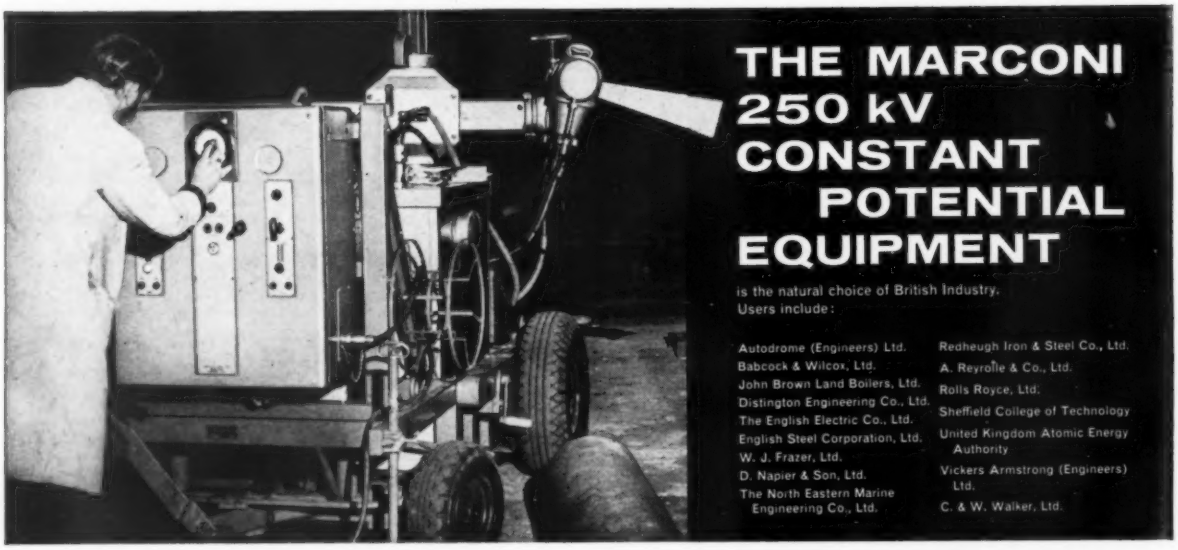

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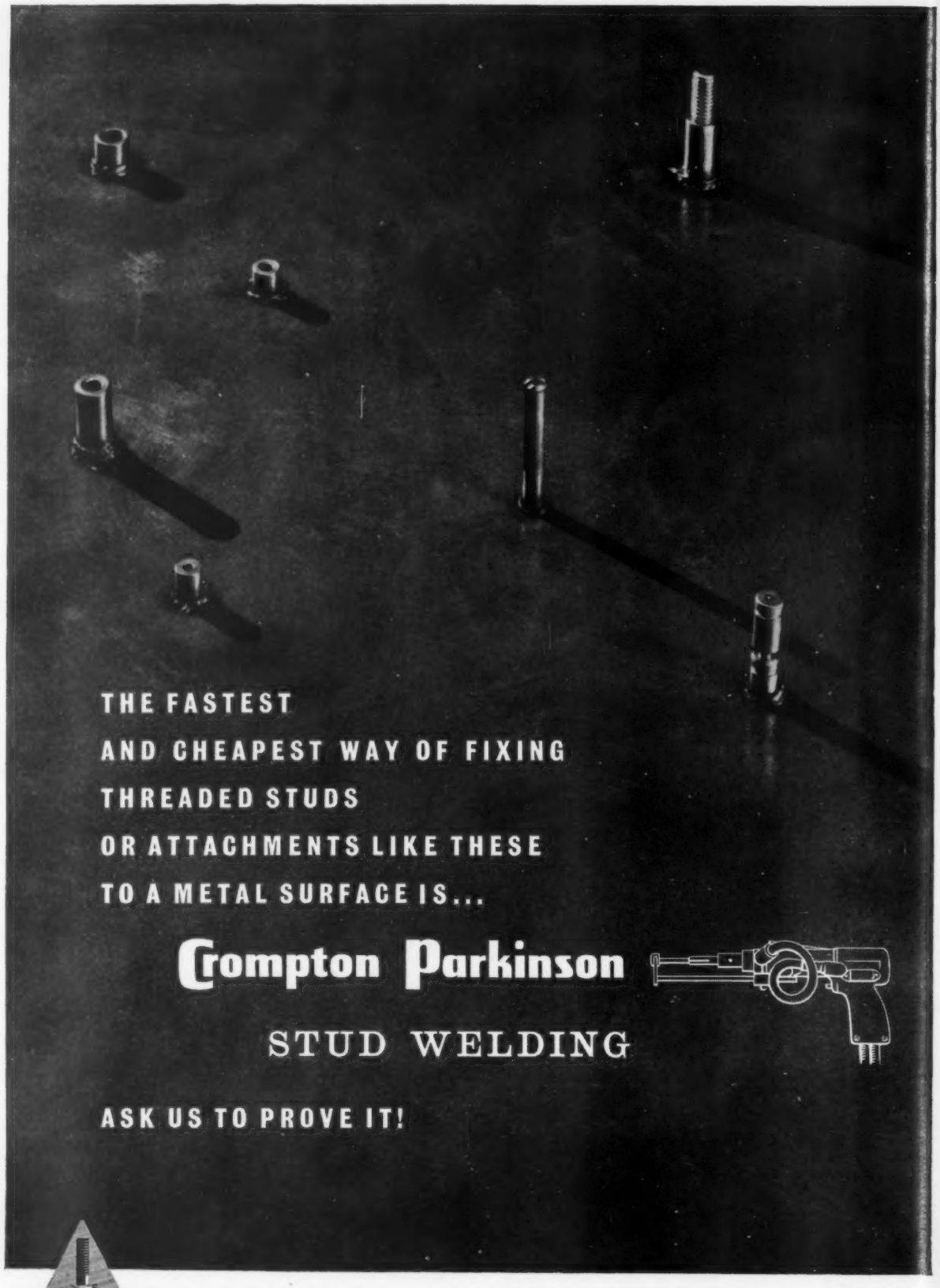
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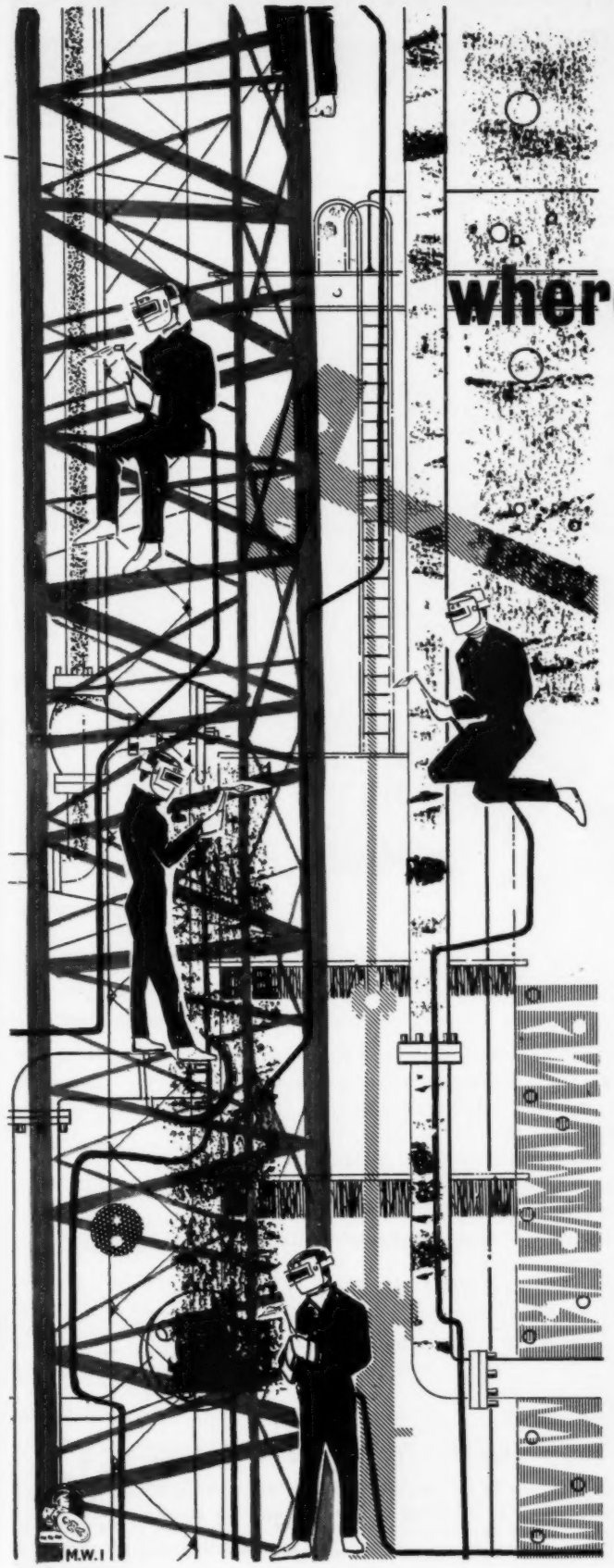

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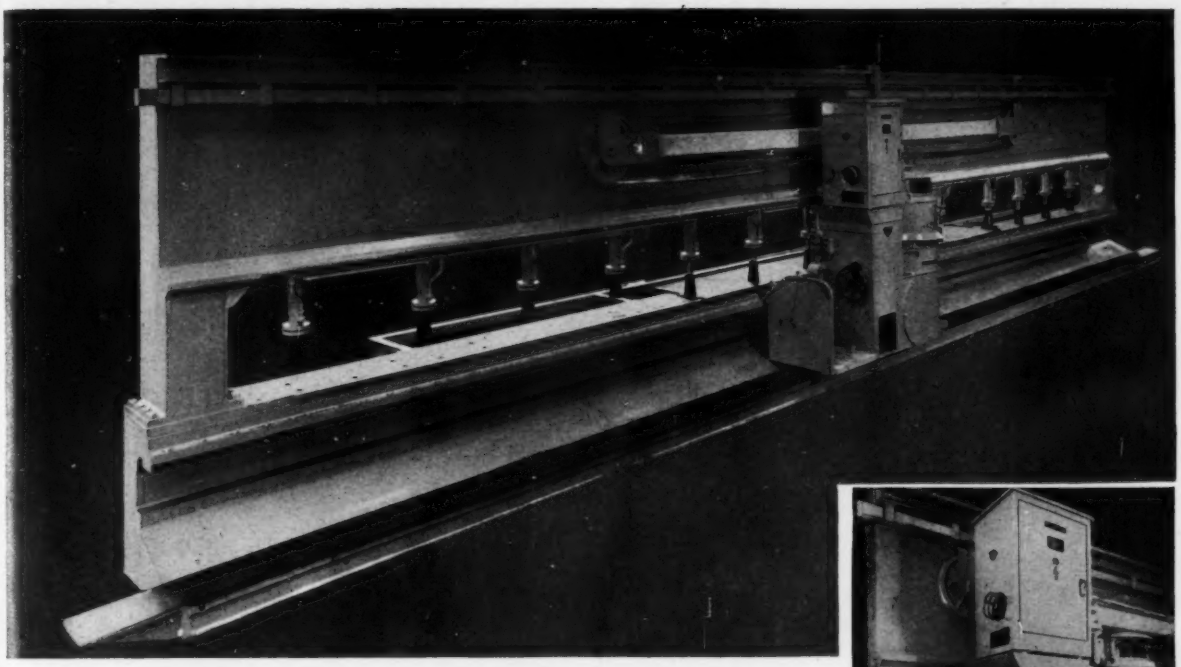

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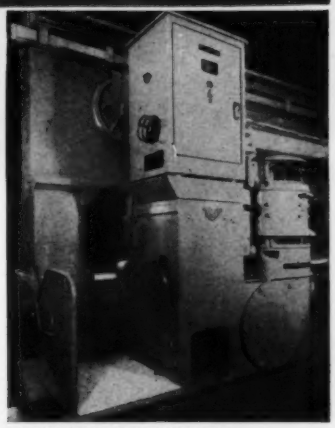

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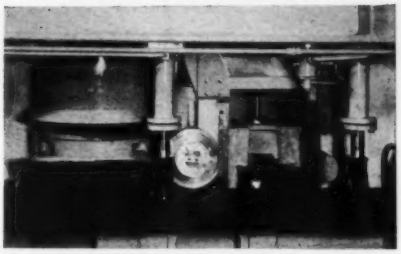

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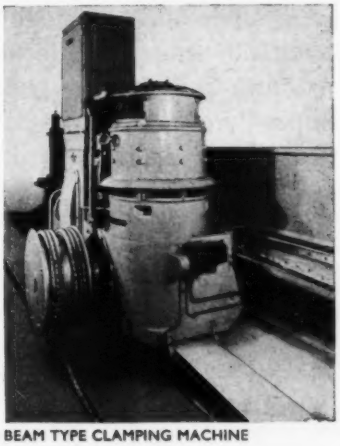

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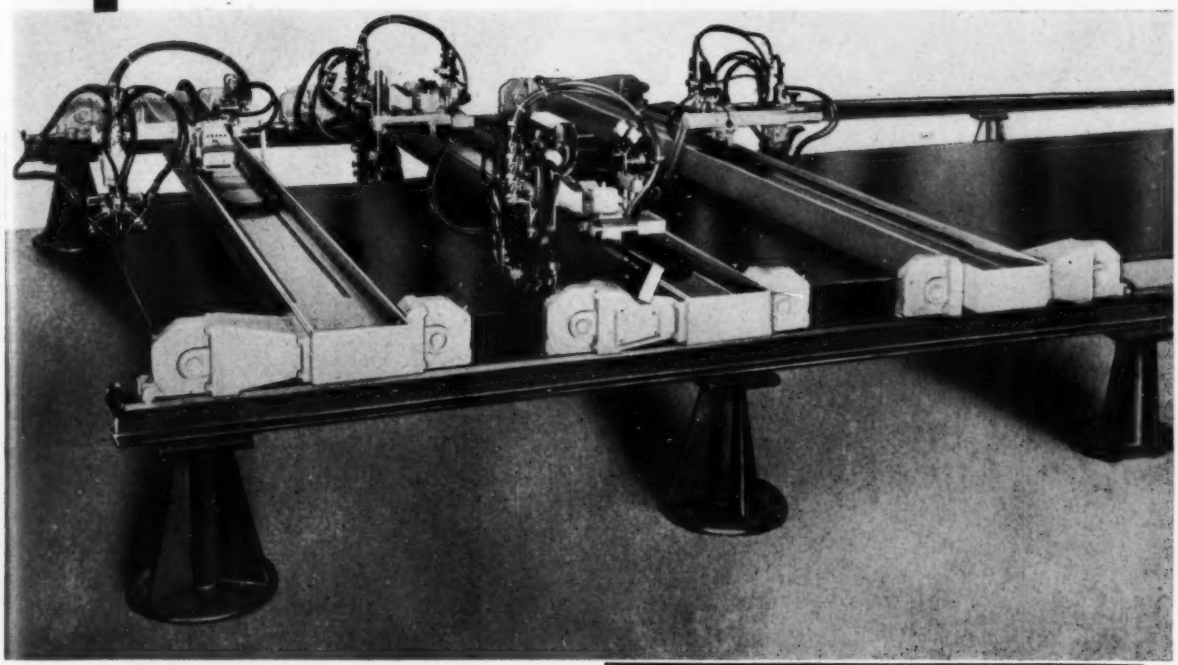

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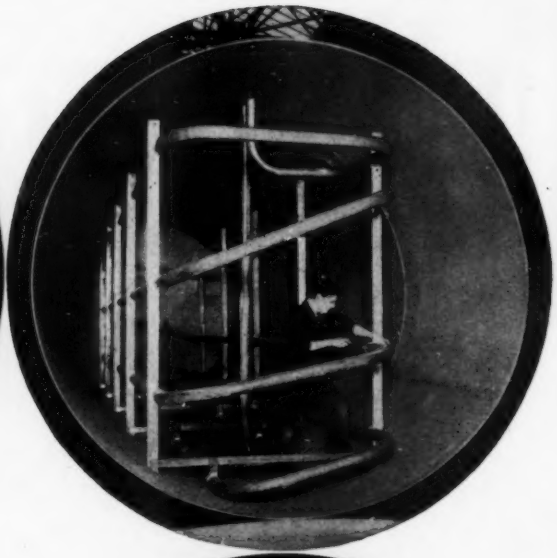

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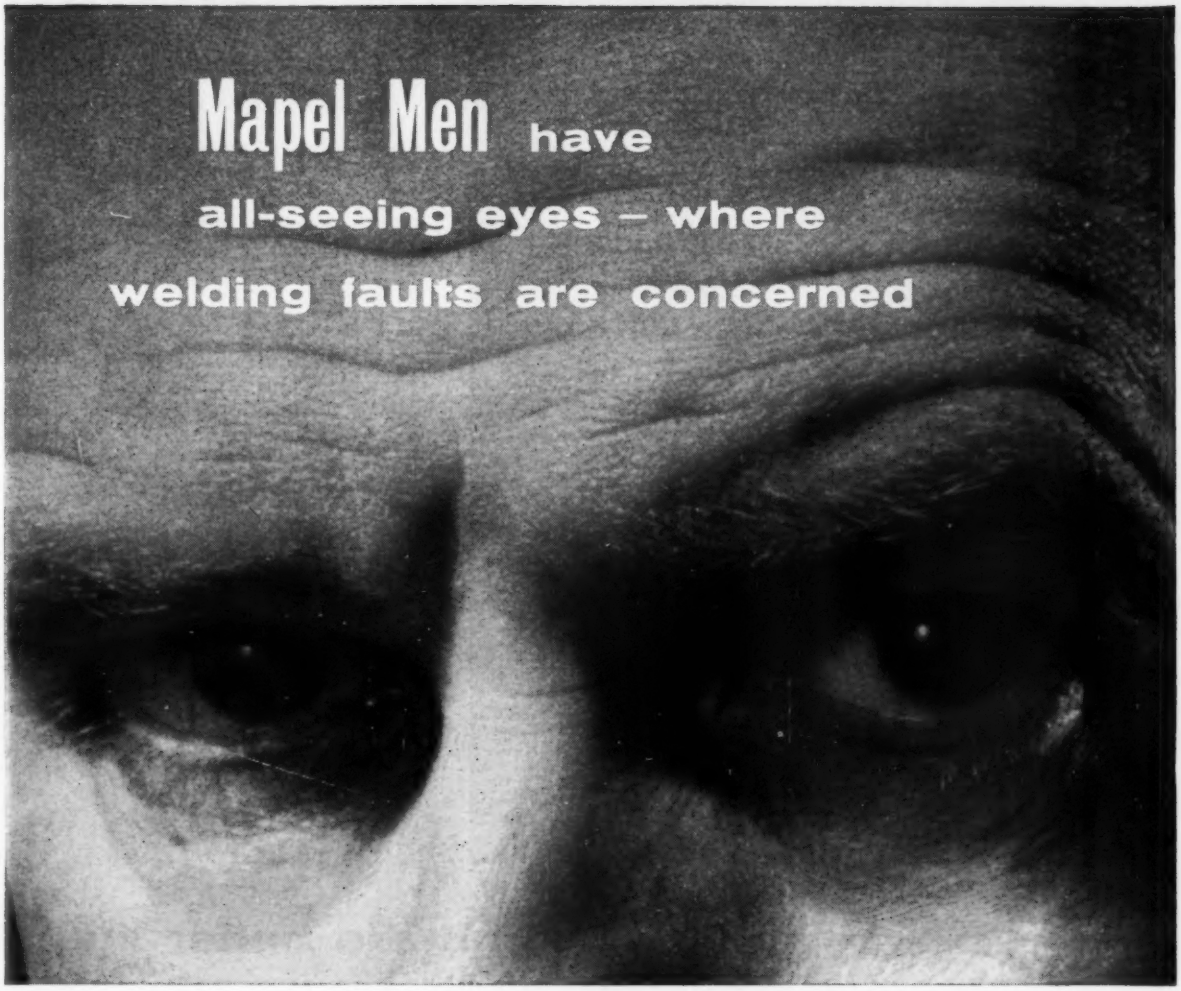

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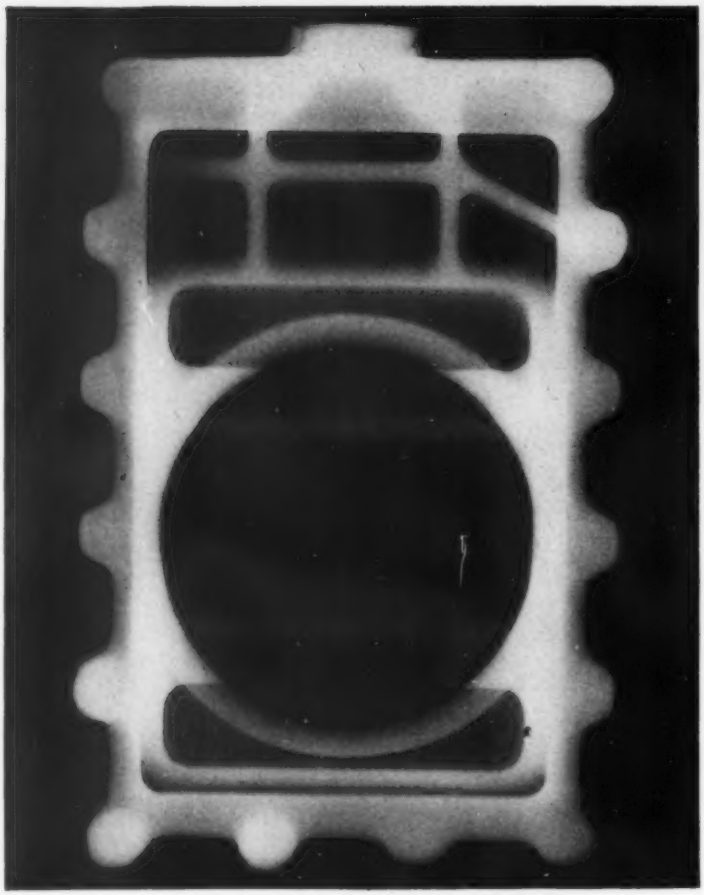

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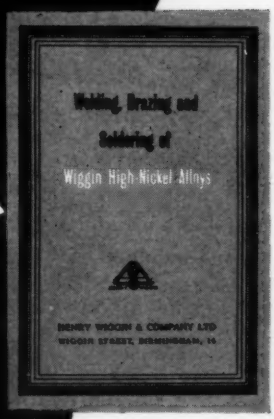

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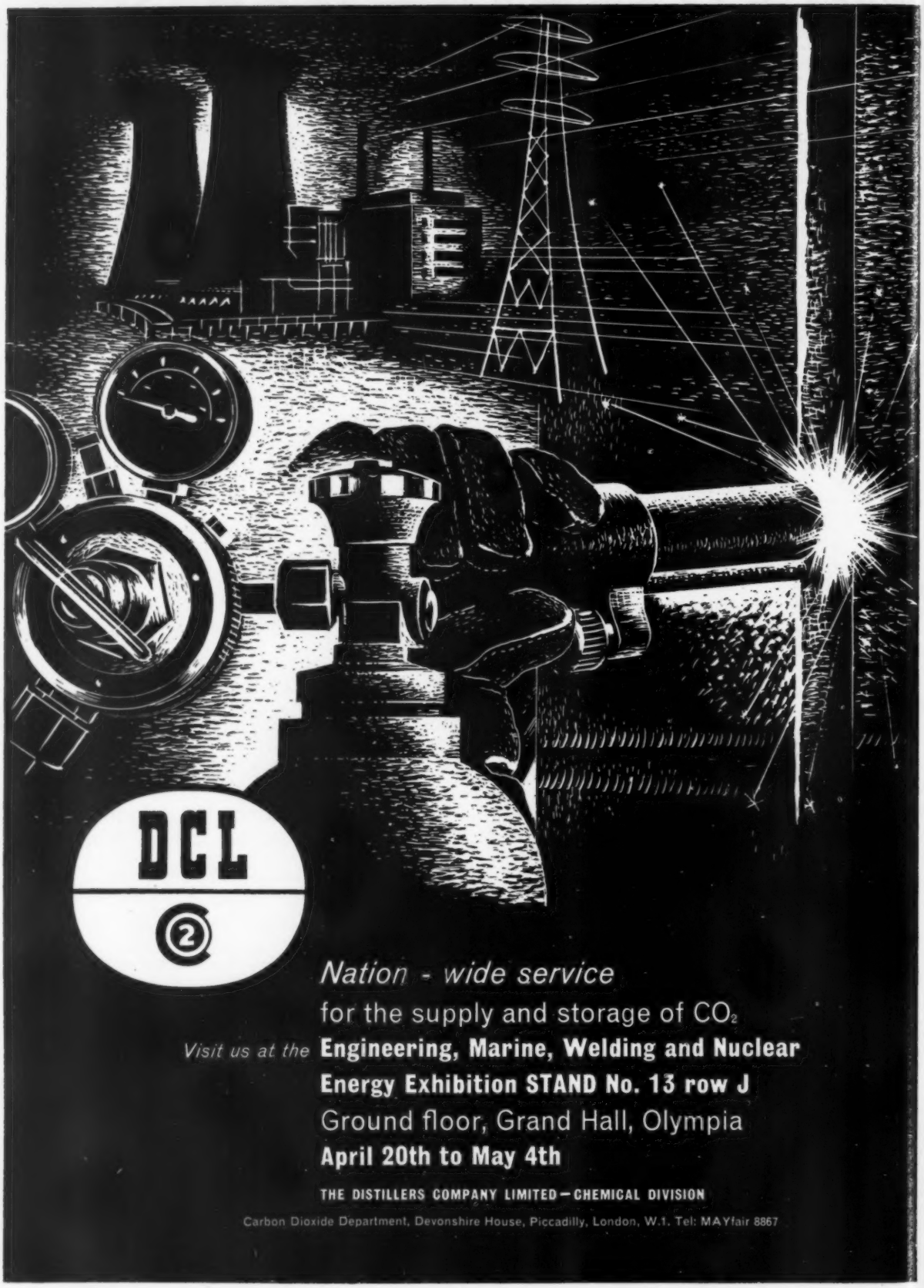
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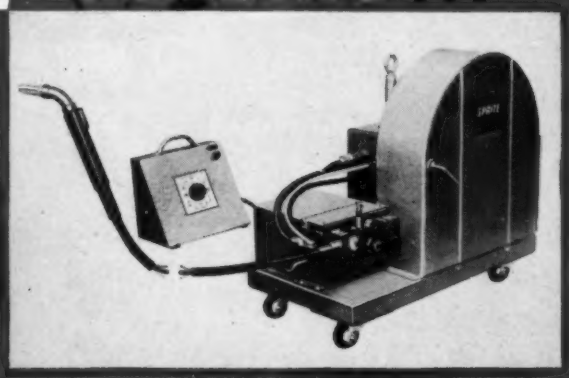

The Lincoln SPRITE CO_2 Welding Unit, showing the Remote Amperes Control Box for 'on the spot' control of welding current and the Lincoln FW.1 CO_2 Hand Welding Gun.

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OFFICIAL JOURNAL OF THE INSTITUTE OF WELDING AND THE BRITISH WELDING RESEARCH ASSOCIATION

Incorporating the *TRANSACTIONS* of the Institute and *WELDING RESEARCH*

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APRIL 1961
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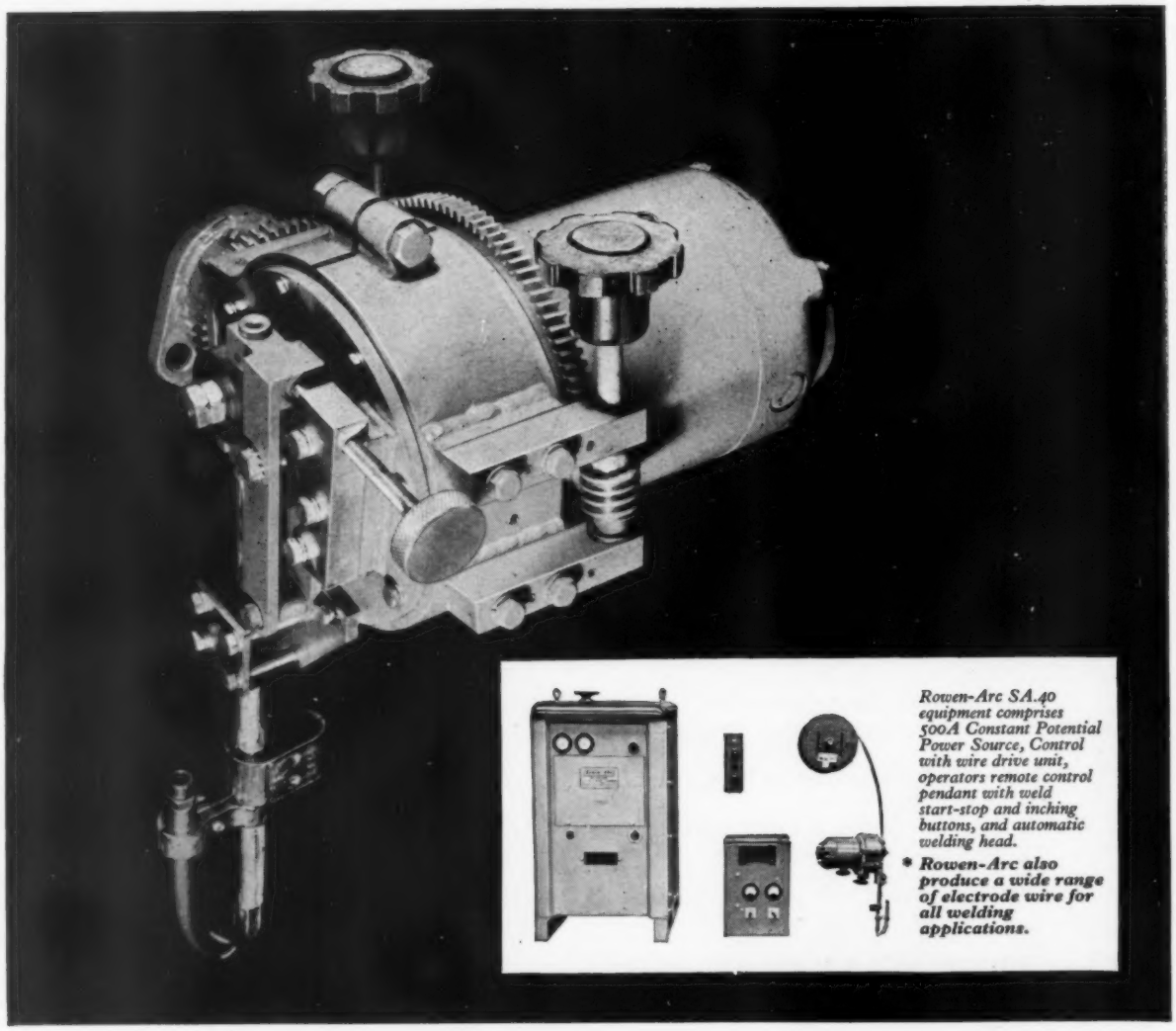
the automatic choice for successful welding



Rowen-Arc SA.40 equipment comprises 500A Constant Potential Power Source, Control with wire drive unit, operators remote control pendant with weld start-stop and inching buttons, and automatic welding head.

* ***Rowen-Arc also produce a wide range of electrode wire for all welding applications.***

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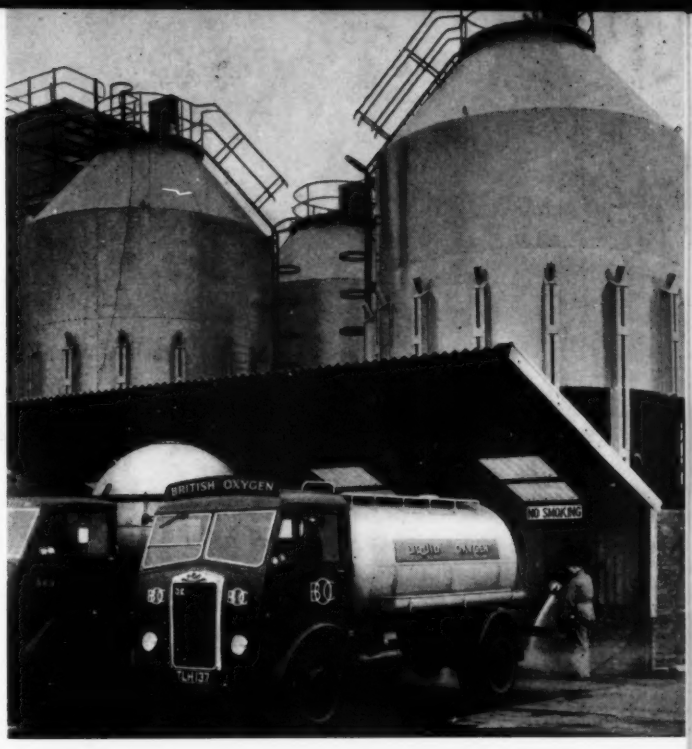
Olympia Preview

British Oxygen Show Wide Range of New Machines and Equipment

New Automatic Line Tracing Device: BOC's Latest Portable Cutting Machines: Latest Advances in Electric Welding:

NEW EQUIPMENT—new techniques—striking advances in industrial gas production and distribution—and a greater service to industry than ever before—all are exemplified on the British Oxygen stands at the Engineering, Marine Welding & Nuclear Energy Exhibition at Olympia this year.

Today—Oxygen—lifeblood of industry—is being produced in unprecedented quantities. Steelmakers alone are using more than a thousand tons a day—most of it drawn from British Oxygen tonnage plants installed at or near the steelworks. By the end of 1962 they will be using three times as much.

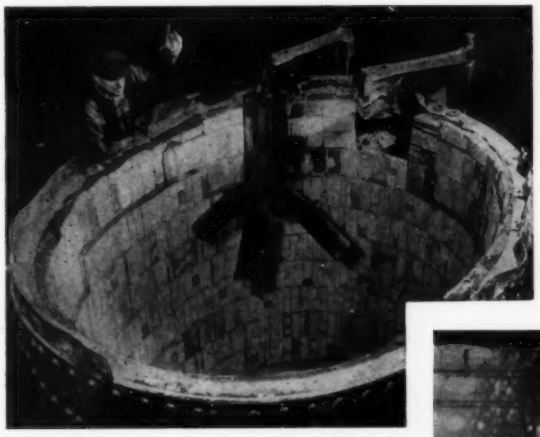


Liquid oxygen storage tanks and tankers at the Middlesbrough Works.

How BOC are successfully meeting industry's constantly growing demand for oxygen is typified at the exhibition by the model of an oxygen-producing plant on Engineering stand G.5. This is supported by illustration of the comprehensive distribution system and service offered by British Oxygen to all their customers, whether they buy by the ton or by the cylinder.

British Oxygen's acknowledged expertise in the distribution and use of Propane in industry, is illustrated by examples of bulk and portable cylinder supply systems. Propane has taken a firm place alongside acetylene as a most efficient fuel-gas in many cutting and heating applications.

Hand equipment for cutting, welding and heating is highlighted on British Oxygen's Light Industrial stand W.1. Twin lightweights—the new 'Firefly' handcutting blowpipe, selling at



Being lowered into a 60-ton ladle is the new propane-fed heater designed for drying out and fettling steelworks ladles.

At a large car body works in the Midlands several ST.2 torches are now being used in conjunction with the new slope-controlled rectifier and 'Lynx' wire feed equipment.

BRITISH OXYGEN

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Twin fillet automatic welder

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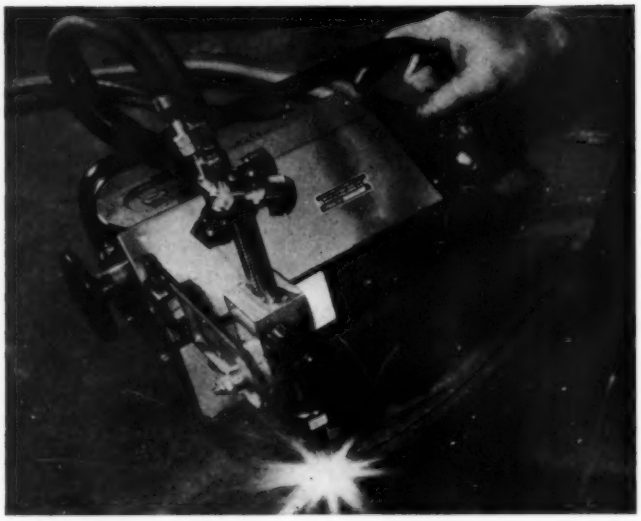
With the new SW.300 spot welding torch access to only one side of a joint is needed. Aluminium is here seen being spot welded with the new equipment.



A new lightweight portable straight line and circle cutting machine selling for under £40, joins British Oxygen's range of small oxygen cutting machines.

just over £7, and, latest from the 'Saffire' range, the lightweight welding blowpipe costing £6 14*s*. 6*d*.—are both designed for efficiency, economy, robustness and ease of operation.

New, too, is an automatic line tracing device. This enables a profiling machine to operate from simple pencil line drawings. Conventional templates are eliminated, thereby saving time and money. The new device is demonstrated on the latest 'Bison' profile cutting machine.

Also a newcomer—a lightweight portable straight line and circle cutting machine selling for under £40. In joining the 'Bantam 2' in British Oxygen's range of small portable machines, the new machine makes high quality mechanical oxygen cutting available to an even wider range of industries.

Latest 'Alyn' pipecutting machines for branch preparation and pipeline work, are demonstrated. For branch preparation 'Alyn' machines generate the desired profiles from direct basic settings. No conversion or calculation is necessary.

Major advances made by British Oxygen in electric arc welding can be seen on stand W.5, which is devoted entirely to manual, semi-automatic and automatic electric welding techniques. Exhibits include the new slope-controlled rectifier—the MRCS.300—designed for semi-automatic welding using the 'short-circuiting arc' technique. Described by leading car body builders as a major breakthrough in sheet metal fabrication the newcomer is shown used with 'Lynx' wire-feed equipment for welding mild and stainless steels.

Unique slope controlled characteristics of the new rectifier enable selection of conditions to suit any welding application over a wide metal range down to 20 s.w.g., even with excessive gaps, and in any position.

With the new rectifier is demonstrated the revolutionary ST.2 torch, designed particularly for 'fine-wire' welding, and which gives unprecedented accessibility and eliminates operator fatigue. The combination can be used with CO_2 and Argon/CO_2 mixtures, as well as with Argon or Argonox gases.

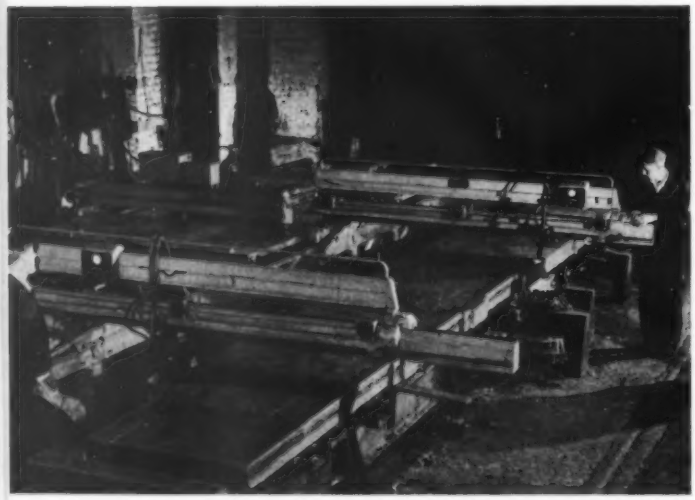
The latest in automatic welding methods is exemplified by a twin fillet welder for scalloped as well as solid stiffeners, fitted with two 'Basic' heads. The heads are adaptable for 'Fusarc/CO_2', 'Unionmelt' or 'Sigma' automatic processes.

Two versions of a new lightweight 225 amp. generator are displayed—one diesel-powered and the other electric mains driven.

A roller bed installation, for rotating cylindrical vessels, is shown in conjunction with the now familiar and widely used ram-type welding boom. With this combination, vessels such as boiler drums, petrol tanks, hot water cylinders and large-bore tubes, can be welded longitudinally and circumferentially under perfect speed control, and the boom can also go inside the vessel.

New among argonarc welding products is the SW.300—a spot welding torch designed to be used with a wide range of electrodes and interchangeable nozzles. It can be operated simply and cheaply by semi-skilled labour. Spot welds can be made with one hand and ..... access to only one side of a joint is needed.

A few examples in a range ..... of products and gases designed to meet the need of every user—large or small. Each product is backed by technical knowledge and experience accumulated by British Oxygen over many years, resources which are placed at the disposal of users throughout the breadth of industry.



Latest 'Bison' oxygen cutting machines are here seen profiling heavy side frames for diesel locomotives.

Welding TECHNOLOGY

SPRING MEETING 1961

Developments in Stud Welding

The first part of the paper deals with stud welded shear connectors, whose comparatively recent advent has created a need for adapting current available equipment to deal with the high stud welding rates required. It has also been necessary to develop a satisfactory technique to ensure a practical commercial proposition.

The second part of the paper is concerned with developments in aluminium alloy stud welding. The consistent production of sound stud welds on these materials had presented complex problems until the research programme described pinpointed the causes and obscure reasons for erratic welding results. Since the adoption of the recommended new techniques, and the introduction of additional auxiliary equipment, a completely new and satisfactory standard has been reached, enabling the stud welding of NE.5 studs to NP.5/6 and similar plate to become a sound proposition.

By D. J. N. Laurie

THE PROCESS of stud welding as such, is already so extensively used, and so widely understood, that it is not proposed to deal with it in its broad aspects. Nevertheless, in recent months there have been marked developments in two fields, each of which offers both technical and topical interest.

Structural Engineering

In the structural engineering industry, stud welding finds its place by virtue of the increasing extent to which the studs known as shear connectors are being used in the construction of many bridges and buildings.

It is not the purpose of this paper to go into the question of structural design, but a broad knowledge of the function of the shear connector is necessary to an understanding of the welding problems involved.

In general terms, a shear connector may be regarded as a form of welded attachment (Fig. 1) for the purpose of uniting a steel beam, or member, with the concrete slab which is subsequently cast onto the beam. The quantity and disposition of shear connectors to be welded to any given beam are entirely design considerations, and do not affect the welding aspect.

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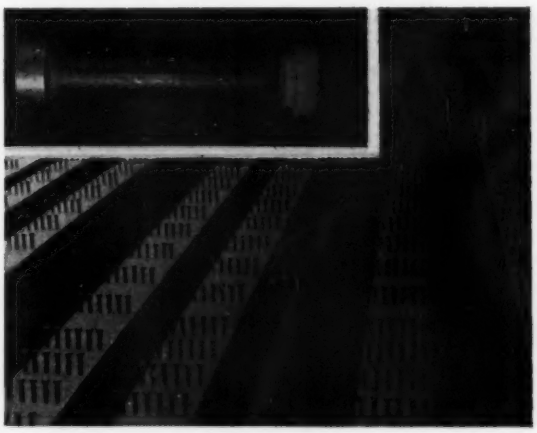
Fundamental problems

The fundamental welding problems involved are twofold. In the first place, much higher welding speeds than are normal for this diameter of stud must be obtained to meet the commercial requirement. In addition, as



1—*Shear connectors on approach girders for Walt Whitman Bridge, Philadelphia. (Inset—shear connector and ferrule)*

substantial numbers of shear connectors have to be welded very close to the edge of the top flange of the beam, there is an incipient tendency to arc blow.

At this point it is useful to visualize the task as it appears to the welding engineer in charge of the project. There will be a steel beam whose top flange dimension may be anything from 6 in. to 36 in. wide, and up to 75 ft or more long. On this flange are to be welded transverse rows of up to perhaps 6 shear connectors of either $\frac{3}{4}$ in. or $\frac{7}{8}$ in. dia., with spacing between the rows ranging from 6 in. to 36 in.

This finished flange will have welded onto it some hundreds of shear connectors so conveniently spaced that extremely high welding speeds are inevitable. Furthermore, it is almost certain that a number of additional beams will be waiting alongside for similar treatment.

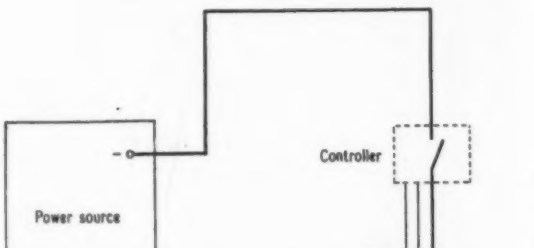
It is now seen that the weld speeds called for on an application of this nature will be substantially higher than those on fabrications or components on which the welding of studs of these large diameters is normally carried out.

Cable considerations

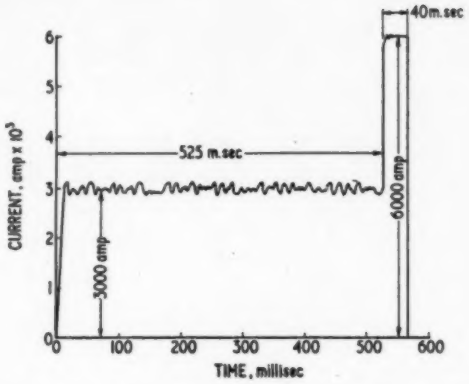
Without suitable equipment modification, the first consequence of this vastly increased weld rate will be overheated cables.

A logical first step, therefore, is an increase in cable section. The consequent drop in resistive value will, of course, curb temperature rise, and will also reduce the voltage drop in the cable to an acceptable level when long extension cables are in use. The recommended increase in cable section can be applied throughout the main welding current circuit with the single exception of the short length which is part of the handtool assembly. However, since the handtool is, in any case, prone to the heat affect of arc radiation and of heat transfer from the studs, it is normal practice to employ the expedient which is already widely known in arc welding circles, namely, to use two handtools alternately for periods of 20–30 min, allowing one to cool while the other is in use.

One of two methods may be employed to increase the current carrying capacity of the earth cables. It is possible either to use a single earth cable of increased cross-section, or to use twin cables of standard section which would then be connected one to each end of the work piece. Since the second method has additional practical benefits in providing a balanced earth, it is the one invariably adopted.



2—*Simplified stud-welding circuit*



3—*Oscillogram of stud-welding current without subsidiary contactor*

Cable temperature rise is largely dependent on four main factors:

(i) The comparatively high frequency at which welds are to be made
(ii) The time taken for each weld, which is predetermined and fixed at an optimum setting
(iii) The resistance of the cable in circuit, which has already been dealt with by an increase in section
(iv) Welding current.

A study of the basic stud welding cycle should now be made before considering the steps which may be possible for modifying the current conditions (Fig. 2).

Weld cycle

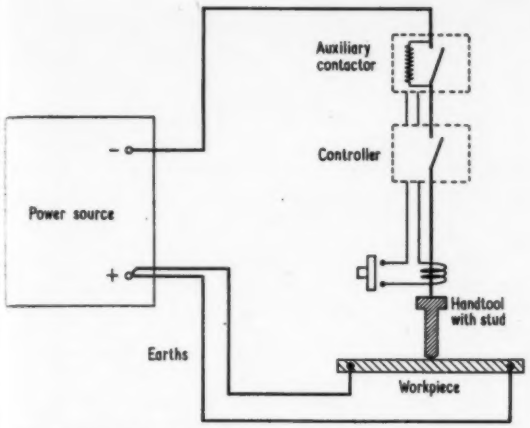
Briefly, the simplified sequence of operations can be enumerated as follows:

(*a*) The cycle is initiated by operating the press switch on the handtool
(*b*) In consequence, the welding circuit is closed, and the stud retracts from the plate
(*c*) An arc is drawn between stud and plate for a period of time pre-determined by the controller setting
(*d*) At the end of this period, and while the current is still flowing, the stud is returned to the molten pool
(*e*) Approximately 40 milli-seconds later the main contactor breaks, thus interrupting the welding circuit, and the cycle is completed.

This sequence is illustrated by the oscillogram shown in Fig. 3. The peak represents the brief and undesirable period during which short-circuit conditions prevail, and current values approach double those which apply during the arc period.

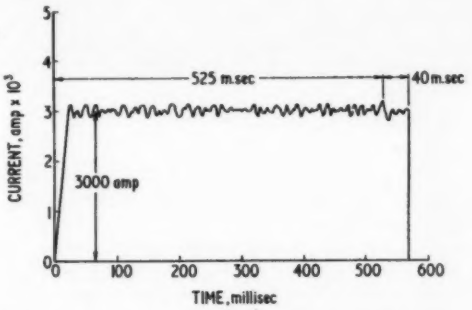
Subsidiary contactor

To eliminate this effect, a unit referred to as a subsidiary contactor is introduced to prevent current rise during the short circuit period. This unit consists of an additional contactor bridged with a resistance, whose value approximates to that of the arc. It is introduced into the circuit between the negative output terminal of the welding power source and the



4—*Simplified stud-welding circuit with subsidiary contactor*

ontroller unit (Fig. 4). The subsidiary contactor is losed during the arc period, and is set to open at the nstant the stud is returned to the plate. In these onditions, the resistance across the subsidiary con- actor is introduced into the main welding current ircuit, so preventing the current rise which would otherwise occur during the final period of the weld ycle (Fig. 5).



5—*Oscillogram of stud-welding current using subsidiary contactor*

Before the introduction of the subsidiary contactor, the main contactor, when it opened during the short circuit period, was called on to break a current of something approaching 6,000 amp for a $\frac{7}{8}$ in. dia. shear connector. Since this peak demand is approximately halved by the introduction of the subsidiary contactor it can be calculated that the cable heating effect due to each stud weld made is thus reduced to a figure approaching 80% of the original value. It will be apparent also that the life of the main contactor tips is very considerably extended by the use of the auxiliary unit. In service, it has been found that main contactor tip life is, in fact, increased by about three times.

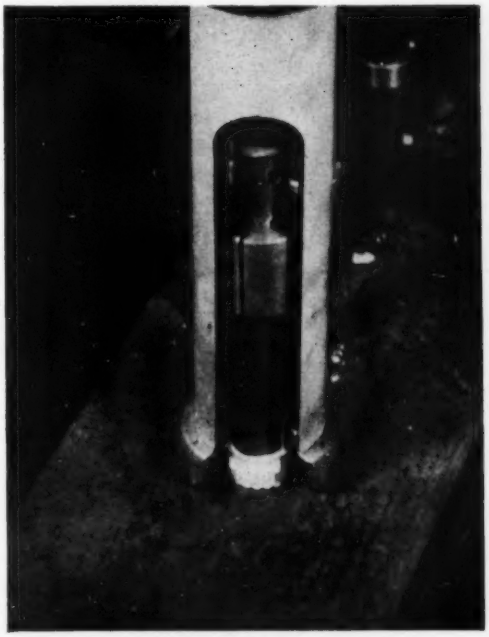
Arc blow

The effects of arc blow, referred to previously, are extremely detrimental to weld quality. Fortunately, the solution of the problem is both simple and practical; experience has shown that the use of a heavy plate

6—*Saddle bars for counteracting arc blow*

placed along the edge of the beam flange near to the welding position is completely effective.

Again, in practice, this is usually accomplished by using two sections of plate held apart to the same dimensions as the width of the beam by one or two flat saddle bars tack welded onto the plate (Fig. 6). By



7—*Open-sided ferrule holder*

this means the complete unit can be slid along as welding proceeds from one end of the beam to the other.

Conclusion

By the combined use of increased cable sizes and the subsidiary contactor unit, the welding rates demanded by industry have been made possible. Additional small modifications were necessary to the handtool attachments, in particular to the chuck which was designed to take the head of a shear connector, and a special ferrule holder cut away on one side to allow removal of the handtool from the side of the shear connector after welding (Fig. 7). Apart from these items, the equipment used is completely standard in all respects.

Developments in Aluminium Alloy Stud Welding

Another important sphere in which considerable development has taken place in recent years, particularly in Great Britain, relates to the stud welding of aluminium alloys of the N.E.5 and N.P.5/6 types containing 3–5% Mg. These are extensively used in shipbuilding and other industries. Although much of the research has been on these specific materials, the results, in general, would appear to be applicable to similar alloys with smaller percentages of magnesium, where there are no other alloying elements present in significant quantities.

At this point it may be of value to consider the state of stud welding on these alloys before the introduction of these recent developments.

Using mild steel stud welding as a basis for comparison, optimum conditions for this material produce the perfect weld, with gradual deterioration in weld quality if conditions are varied either below or above optimum. It is important that there is a consistent relationship between weld quality and weld settings when working with mild steel.

In contrast, when welding these aluminium alloys it was possible to produce two or three near-perfect welds, even when the settings were appreciably less than optimum, although with the same settings the welds that followed could be inferior in quality. In other words, the consistent relationship between quality and settings for mild steel has given way to complete inconsistency, and for this reason the results obtained when setting up and carrying out test welds in preparation for production work could be completely misleading.

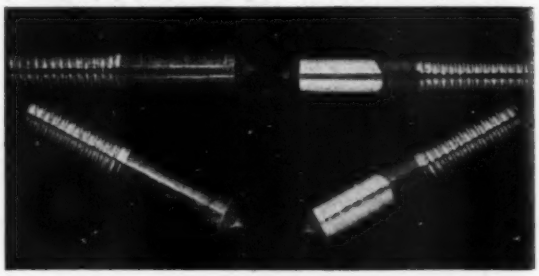
Many industrial users, particularly of the smaller sizes of stud ($\frac{1}{4}$ in. dia. and less), were satisfied with the results obtained, but generally the larger sizes could not be used where strength and reliability were critical.

The stage has now been reached where precise time intervals, current settings, material conditions, and polarity are known. Whilst this information in itself was sufficient to produce substantial improvements in weld quality, it soon became apparent that, to emulate the results obtainable with mild steel, the introduction of a protective atmosphere was necessary. However, before describing this stage, the course of the development work leading up to it will be of interest.

Improvement of weld quality

During the earlier attempts at improvement, one recurring fault contributing to inconsistency and low strength was the presence of entrapped impurities in the weld. These formed areas of varying size in the fusion zone and reduced the effective cross-sectional area of the weld. Argon shrouding was introduced at this stage but did not eliminate the fault. Further investigation was made by using high-speed photography, and by sectioning and examining a series of welds.

It became evident that the cause was not oxide formed during the weld cycle, but portions of the existing surface layer which did not break up completely during the arc period. It was found that this was not simply aluminium oxide, but a thin residual of drawing lubricant which had worked into the surface. The prior removal of this layer by machining the stud (Fig. 8) provided the first worthwhile improvement in strength and consistency. The sections

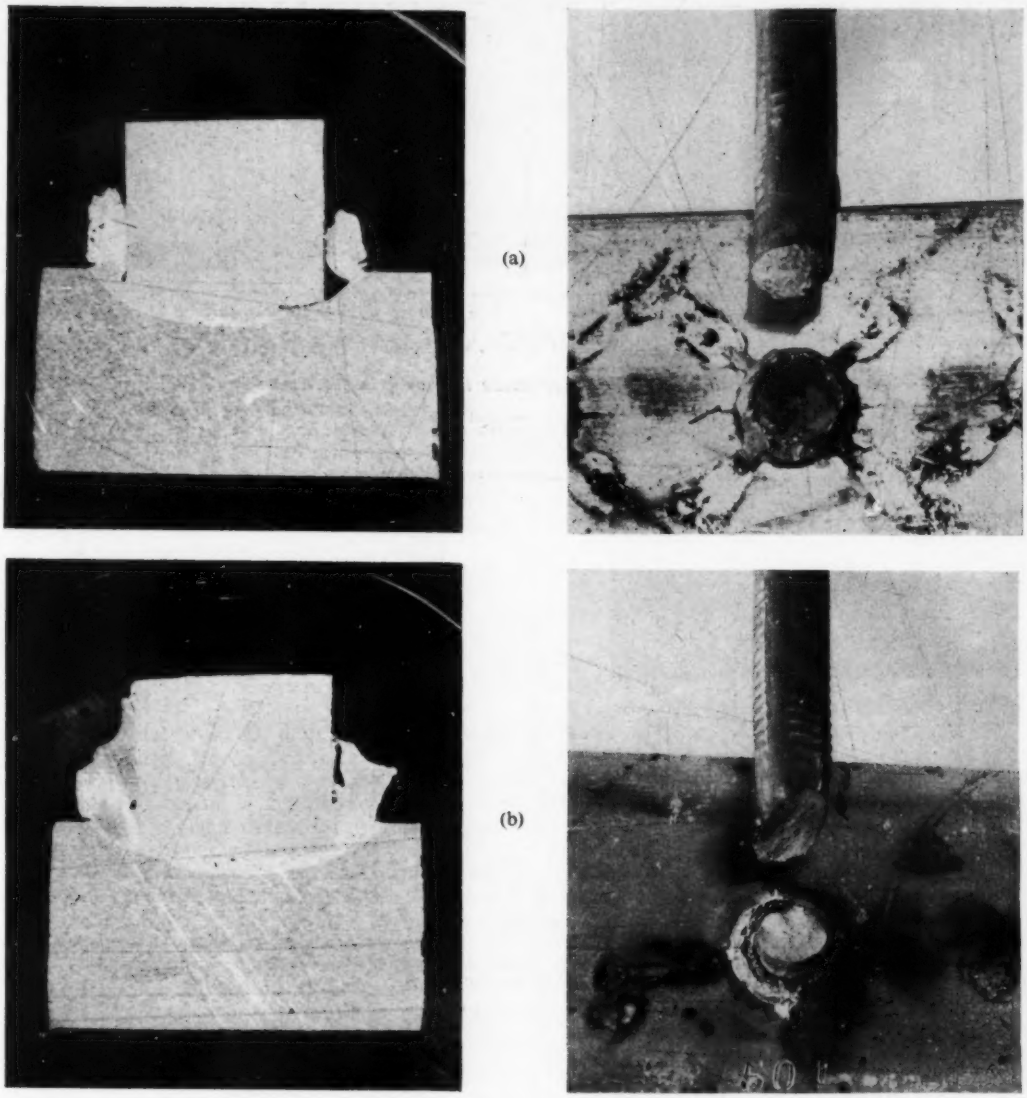


8—Unskimmed (left) and skimmed (right) studs

and photographs in Fig. 9 show the difference in welds made under similar conditions with, and without, the surface skin. As well as a reduction in the number of inclusions, the fillet metal is able to form a bond onto the stud to a greater height. Histograms (Fig. 10) show the improved strength obtained when the stud ends are skimmed. It has since been found, after experiment, that certain chemical treatments can also be used to remove the surface film. This has certain advantages; for example, it does not involve alteration to the shape at the welding end of the stud, which would have certain secondary effects. Further investigation is still being made in this direction.

With the skin removed, argon shielding produced a marked improvement in weld quality. Histograms (Fig. 11) based on tests of $\frac{3}{8}$ in. dia. unthreaded pins illustrate the results obtained. Thereafter, by a series of extended tests, the optimum range of time and current settings was established for this size of stud. It was found that the strength of welds made in all positions under these conditions was always comparable with the strength of the full stud section.

Since the U.T.S. of the rolled and drawn stud material may be expected to exceed that of the cast weld metal, where threaded studs are involved, the strength developed at the fusion zone will always exceed the strength of the smaller area represented by the thread-root diameter. Although the histograms shown were based on tensile tests there was



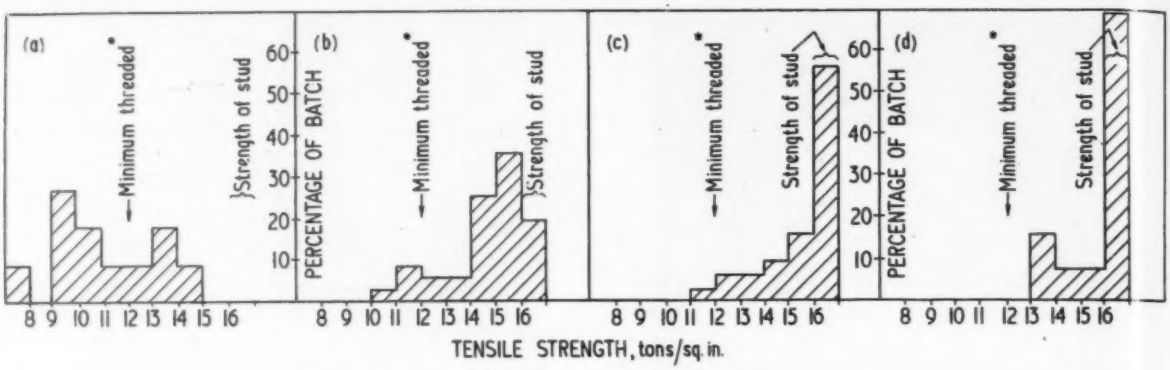
9—(a) *Welds made with unskimmed studs;* (b) *Welds made with skimmed studs*

confirmation of these findings from micro-sections, fatigue and bend tests.

The settings found best for $\frac{3}{8}$ in. dia. studs were extended to higher and lower diameters with proportional adjustments, and similar results were obtained on all sizes up to $\frac{7}{16}$ in. dia. The improvements obtained on $\frac{1}{2}$ in. dia. studs, however, were not sufficient to ensure a minimum weld strength significantly above the thread-root strength. Some detailed investigation into the new factors introduced at this size was clearly required, and a series of test welds was made over a range of current and time settings at both polarities. The specimens produced were then sectioned and examined systematically. In addition, a corresponding series of micro-sections was made for which the weld cycle had been modified to allow the molten stud end and weld pool to solidify before coming together. High speed films were also taken at selected settings at both polarities.

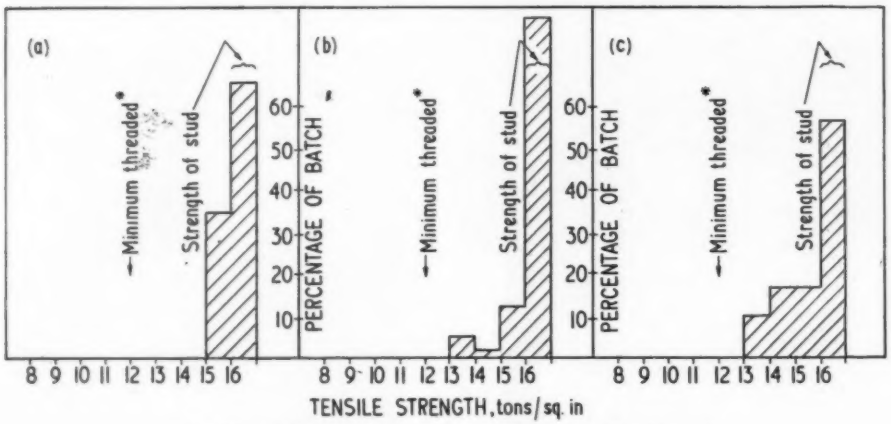
These investigations produced a picture of how changes in current and polarity affected the end shape of the unmolten part of the stud, the degree of porosity produced in the stud end and in the weld pool, and the type and quantity of metal transferred from the stud end to the weld pool during the arc period.

The reasons for the improved results obtained with certain current settings began to emerge more clearly from these tests. The earlier tests on $\frac{1}{2}$ in. dia. studs in these alloys indicated that there were relatively narrow optimum ranges for both polarities. These were quite different for each polarity, and the true optimum was chosen from the best of these two ranges. It may be of



10—*Histograms of results of tensile tests on ⅜ in. dia. studs:*

(*a*) Unskimmed studs welded downhand in air
(*b*) Skimmed studs welded downhand in air
(*c*) Skimmed studs welded 'vertically' in air
(*d*) Skimmed studs welded overhead in air
* Minimum strength to ensure fracture in stud if threaded



11—*Histograms of results of tensile tests on ⅜ in. dia. skimmed studs welded in argon with positive polarity:*

(*a*) Downhand (52 studs); (*b*) vertical (58 studs);
(*c*) overhead (30 studs)
* Minimum strength to ensure fracture in stud if threaded

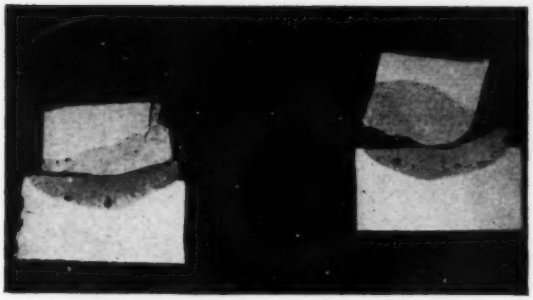
interest to describe some of the changes that were found to occur with increasing current and correspondingly shorter weld times in each polarity for this diameter.

Effects of current and polarity

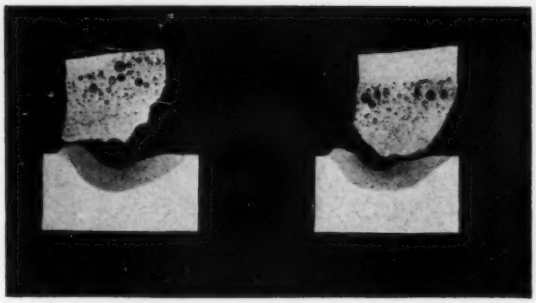
With the stud positive, weld current at 400 amp and using a relatively long weld time (*i.e.* long-time, low-current conditions), a concave end to the unmolten portion of the stud was produced causing gas entrapment and contraction cracking under the centre of the stud on its return to the pool. At this current, the weld pool was only slightly larger than the stud diameter, and severe porosity built up both in the stud end and in the weld pool. However, there was very little metal lost in transfer from the stud end during the arc period. An increase in current improved all these factors but the metal transfer becomes excessive at between 700 and 800 amp. These indications suggested that the 600–700 amp range was most satisfactory, and tests on the completed welds gave full practical confirmation that this was so. The unmolten portion of the stud end can become appreciably heated by conduction from the molten portion during the relatively long arc time. This assists fusion of metal from the weld pool onto the sides of the stud.

The studs which were subjected to the experimental weld cycle, without the final return, showed that the main build-up of porosity was in the weld pool, particularly between the pool and the base metal (Fig. 12). This is, of course, consistent with the movement of electrons at this polarity. This type of porosity will not clear under the action of the returning stud, and it is this residual fine porosity which limits the weld strength obtainable to approximately that of a B.S.W. thread-root cut in the stud.

Various experiments aimed at improving this performance by alterations in arc length, return-spring



12—*Porosity at base of weld pool. Studs not returned. Positive polarity*



13—*Porosity build-up with stud at negative polarity. Studs not returned*

pressure, damping, and ferrule design, did not succeed in effecting any significant improvement.

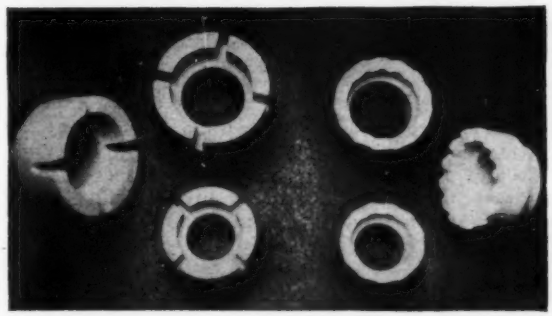
With the stud at negative polarity at low current settings, there was again evidence of severe porosity, concave unmolten stud end, and small pool size. At slightly increased current settings the pool size became adequate. Porosity was much more severe however, even at higher current settings, because the electron flow was from the stud to the plate, the main build-up of porosity in this case occurring between the unmolten and molten metal at the stud end (Fig. 13). Further increases in current again resulted in some overall improvement, but no satisfactory results were obtainable in the range in which there is little metal transfer.

Above approx. 800 amp, however, high-speed films showed that the molten metal leaves the stud end continuously in the form of droplets during the weld cycle. Under these conditions the shortness of the weld cycle, the polarity, and the continuous loss of molten metal from the stud end combine to keep the unmolten portion of the stud comparatively cold. Thus, at these high currents, the weld is formed by plunging a relatively cold, but fairly well shaped stud end into a pool consisting of almost all the molten metal produced. The porosity that has not been released by the metal transfer is then swept aside into the top of the fillet. This leaves sound metal under the stud, but forms little bond above this position. These settings (approx. 1,000 amp with stud negative) in fact provided the best conditions for this size of stud with standard equipment in air, but it will be clear that, even with the degree of forging obtained from the return spring, the molten metal on the underside of the stud alone can never develop the full strength of the wrought shank.

Effects of ferrule design

The ferrule material must, of course, be capable of withstanding the heat of the arc and of intimate contact with the molten metal without introducing impurities or further porosity. As distinct from steel stud welding, the fillet does not tend to form before the two parts meet, and the inside walls of the ferrule act to some degree as an extension of the rim of the pool to guide metal up into the fillet. Ferrules with a limited number of gas escape outlets, extending to the full height of the recess so as to ensure adequate venting for the stud return, are thus required. The

(a) (b)



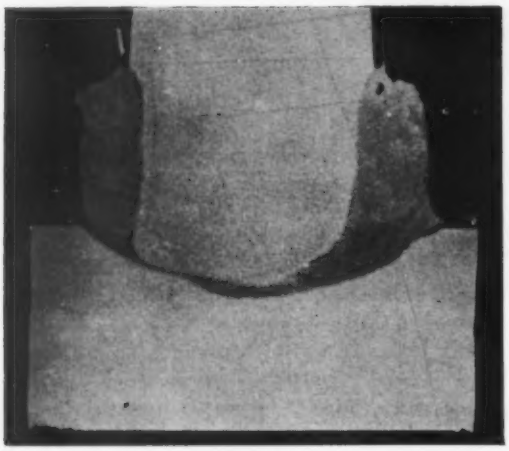
14—*Stud welding ferrules:* (a) *For aluminium alloys;* (b) *for mild steel*

fillets are rather larger than with steel to enable porous metal to be swept from the critical positions and, owing to the high conductivity and low specific heat of these alloys, it is vital that there should be no possibility of a delay in the return of the stud as a result of contact with the bore of the ferrule. Figure 14 shows ferrules for use with these alloys beside corresponding ones for mild steel. The rapid cooling also provides the reason for the use of the 'hot plunge' weld cycle for these materials, in which the current is not cut off until the weld cycle is completed.

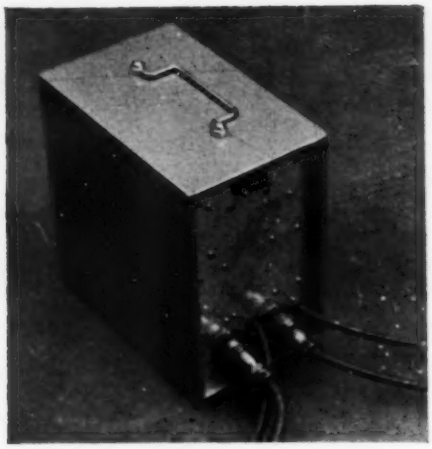
With the standard cycle, already stated, neither positive nor negative stud polarity provided conditions which could ensure really satisfactory strength in $\frac{1}{2}$ in. dia. studs of these alloys. In *air*, negative stud polarity at about 1,000 amp provided the best condition, but with *argon*, the 650 amp positive stud condition was slightly better.

Methods of improving stud heating

After the development of the above theory of the mechanisms involved, attempts were made to improve the heating of the stud end when at negative polarity, without altering the weld cycle. The use of alloys containing a small percentage of beryllium (which has been found by workers at the B.N.F.M.R.A. to increase the surface tension in the molten metal), was tried with the object of holding the molten metal in contact with the stud for a longer time. Alternative end shapes for the stud, and attempts to change the shape and motion of the arc by magnetic and electrical influences, have also been tried without success.



15—*Section of weld made with preheated stud*



16—*Automatic preheating unit*

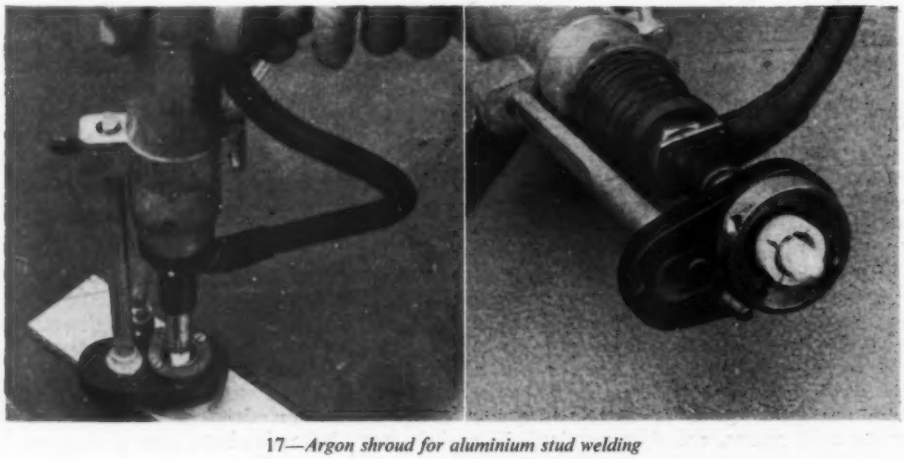
One promising line of enquiry was opened as a result of tests using fairly large particles of iron powder scattered loose in the weld zone. High-speed films showed that these particles were moved rapidly about through the arc (becoming molten) and up around the stud end where they transferred some of their heat to the stud sides. Tensile and bend tests confirmed that there was a general improvement in strength compared with results from welds made without the powder.

This loose powder method was obviously not commercially practicable in that form. Aluminium alloy studs are metallized at the welding end with a thin coating of zinc to reduce the porosity in the weld. Replacing this by metallizing with iron did not bring about the same result as using the loose powder, and actually produced an appreciable reduction in strength; and after other attempts to make it commercially feasible the use of iron powder was abandoned.

To confirm the theory which had now been built up, relating to the mechanisms of weld formation, studs were preheated to 150°–200°C. and then welded at negative polarity at high current. Sections revealed an immediate improvement in the fusion of the fillet to the sides of the stud. Figure 15 shows an example of the excellent results obtainable with ideal settings. The superheated weld metal has made a good bond far up the sides of the stud, so that the combined shear and tensile strength of the weld metal is greater than the tensile strength of the wrought shank. Since it was not found possible to produce welds consistently with a minimum strength substantially above that of a $\frac{1}{2}$ in. dia. threaded stud with the standard cycle, it seemed logical to develop a weld cycle which incorporated a means of automatically preheating the stud.

Separate preheating has the advantage that the whole 'heat-sink' of the stud is adequately filled, so allowing the fillet metal to fuse to it satisfactorily. Where, on the other hand, preheating is done by means of an arc, the time taken to bring the critical zone to an adequate temperature will depend on the current value selected. To prevent any appreciable melting at the weld area during this part of the cycle the current must be kept down to a suitable level.

The standard welding cycle, of the type normally



17—*Argon shroud for aluminium stud welding*

used with aluminium alloys, starts with a pilot-arc of about 13 amp with a duration of a few milli-seconds. The pilot-arc time was extended to provide preheat, but the time necessary was about 8 sec, and this was too long to be acceptable in practice. To overcome this difficulty an auxiliary unit was developed providing a 70 amp preheat current, which allowed the time to be reduced to 3 sec. By using argon shrouding in conjunction with this unit welds can be produced in all positions with an adequate strength margin over the threaded stud. This preheat unit is interconnected with the standard controller and is completely automatic (Fig. 16). The argon shroud used for aluminium alloy stud welding is shown in Fig. 17.

Larger sizes of studs still provide a further challenge, but some work on these has already been done, and it would appear that the general principles of the mechanisms involved still apply.

Acknowledgments

The author expresses his appreciation to J. G. Stokes, J. R. Davies, and others who subscribed to this work.

A Note on Flame Spraying Developments

By Lloyd Manuel

The author briefly reviews recent applications of the wire spraying, powder spraying, and plasma flame spraying processes and describes the relative advantages of these processes.

ONLY four or five years ago nearly all the metal spraying of worn or incorrectly machined parts was undertaken by the wire metallizing process. In most cases the selection of wire to be used was from a simple list of common engineering alloys (Table I).

Table I

Wire for metal spraying

Metal	*Rockwell Hardness*
*Sprabronze AA	B78
*Sprabronze TM	B50
Metco Copper	B32
*Metcoloy No. 1 (18·8 stainless)	B78
*Metcoloy No. 2 (High chrome stainless)	C29
*Sprasteel LS (Low shrink)	C25
*Sprasteel No. 10 (0·10% C)	B89
*Sprasteel No. 25 (0·25% C)	B90
*Sprasteel No. 80 (0·80% C)	C36
Metco Nickel	B49
Metco Monel	B39
*Sprabond Wire (Molybdenum)	C38

* Metco Ltd. are registered users of these trade names.

Today, three processes are available to the metallizing engineer; wire spraying, powder spraying, and plasma flame spraying. The range of materials for spraying now includes hard-facing alloys, ceramics, and even very high melting point metals such as tungsten.

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The writer recently visited a contract metallizing firm where batches of worn pump sleeves were being processed. One batch was to be sprayed with stainless steel, another with a Ni–Cr–B–Si alloy, and another with alumina (Al_2O_3). All were to withstand similar conditions in service. So far, little work has been done to evaluate these very different materials, and decisions for their use are frequently based on the process cost.

There is no doubt that wire spraying will continue to be the most commonly used process for metallizing components which have been worn or incorrectly machined. It has the great advantage of low cost and simplicity of application, and the virtue of being a 'cold' process.

1—*Wire spraying armature bearing*

2—Powder spraying abrasion-resistant deposit

Figure 1 illustrates the metallizing of a journal bearing by the wire process. In this example the major cost factor would be the value of the metal deposited (a 12% Cr steel). Such a component could not, in practice, be treated by any other process.

Generally, therefore, the powder and plasma flame spraying processes should be considered where wire sprayed deposits are unsuitable. These can be very briefly summarized as:

(*a*) Where the deposit is subjected to severe abrasion or point impact
(*b*) Where corrosion resistance or extreme resistance to wear is desired
(*c*) Where high temperature resistance is required.

Sprayed deposits can readily be produced to meet these factors, by the powder spraying process (Fig. 2), using hard-facing alloys or ceramics (Table II).

Ceramics, such as alumina, can resist wear to a very high degree but they are limited to applications where they will not be subjected to impact or abrasion.

Hard-facing alloys have been especially developed to withstand both wear and corrosion, the greatest resistance being given by a Ni–Cr–B–Si alloy blended with a high proportion of tungsten carbide. The only limitation to their use is their higher cost (compared with wire metallizing) and the necessity for fusing the deposit to the base, after deposition, at a temperature slightly above 1000°C.

Whilst plasma flame sprayed deposits, at this stage of their development, are of little value for salvage or maintenance work the physical and metallurgical properties of the coatings are generally superior to those of conventional flame-sprayed coatings. These include reduced porosity, improved bond and tensile strengths, less oxide content in the case of metal, and high density. Coating densities reach to 98% of the theoretical values and are easily controlled. These factors will undoubtedly widen the industrial use of plasma-sprayed coatings. For example, pure tungsten and tungsten carbide can be applied to almost any base material with densities of about 95%.

In general, most inorganic materials that can be melted without decomposition can be applied by this process. Others now in development work include: tantalum, palladium, platinum, zirconium diboride, columbium, hafnium, vanadium carbides, and refractory borides of hafnium and cerium.

Melting points of various spraying materials are given in Table III. There is considerable discussion on the actual values but the table is presented for general information.

The very great range of operating temperatures that can be produced, the variety of materials that can be sprayed, and the basic economies of the process would seem to limit possible applications only to the imagination of the designer and research development engineer. Applications already include the spraying of rocket nozzles and nose cones and other parts subject to extreme thermal conditions, such as crucibles for high melting point materials. In the electronic industry parts for large vacuum tubes have been successfully coated, and in the chemical field considerable work has been done with catalytic as well as protective coatings.

Table II

Hard-facing alloys and ceramics: analyses, %

Alloys	*Tungsten Carbide Aggregate*	*Fe*	*Ni*	*Cr*	*C*	*Si*	*B*	*Cu*	*Mo*	*Co*
12C		2·5	Bal	10	0·15	2·5	2·5			
15C		4	Bal	17	1·0	4	3·5			
16C		2·5	Bal	16	0·5	4	4	3	3	
18C		1	27	19		4	3		6	40
32C	80	0·8	14	3·5	0·1	0·8	0·8			

Ceramics	*Aluminium Oxide*	*Titanium Oxide*	*Zirconium Oxide*	*Calcium Oxide*	*Silicon Dioxide*	*Others*
101	Bal	2·5				
105	Chemically Pure					
201	0·5		93	5	0·35	Bal

Table III

Melting points of spraying materials

Materials	*Melting Point, °F.*
Aluminum Oxide	3772
Calcium Zirconate	4253
Chromium	3430
Chromium Carbide	3434
Ceric Oxide	4712 (approx.)
Cobalt	2723
Cobalt-Zirconia (blend)	2723–4892
Magnesium Zirconate	3848 (approx.)
Molybdenum	4748
Nickel	2650
Nickel–Alumina (blend)	2650–3772
Titania–Alumina (blend)	3344–3772
Titanium Oxide	3344
Tungsten	6170
Tungsten Carbides	5198
Zirconium Oxide (stabilized)	4712
Zirconium Silicate	4388 (approx.)

SPRING MEETING 1961

Foil Seam Welding

In contrast to the normal lap seam resistance welding process foil seam welding enables butt joints to be made successfully in sheet metal panels. The principles of the process are described including the means of concentrating the welding heat at the zone of the joint and of applying the correct pressure for welding.

The results of practical experience are given, together with guidance on the suitable methods of sheet preparation, choice of foil, and selection of welding machine variables.

Special welding machines are described and examples are quoted of the advantages of the process when applied to certain types of fabricated construction.

By Dr. Ing F. Busse

Development of the Process

THE advantages of standard resistance seam welding are well-known: a clean seam surface, no distortion, high welding speed, low power costs, no special preparation of the welding edges (provided that the sheet surface, at least at the welding edges, is free of oxide films and scale). But the process has the major disadvantage that it is not possible to butt weld the sheet metal edges instead of lap welding them.

A simple test shows that no useful welding joint is attained if two sheet metal panels, butted against each other by hand, are passed between the two electrode wheels of a seam welding machine. Evidently two prerequisites for successful butt welding are missing: there is no welding pressure in the plane of the sheets at the contact zone of their cut edges, nor is the current generating the welding heat concentrated exclusively on these contact zones. Only the use of an expedient in the form of a narrow thin metal foil results in an excellent butt seam. This welding process was developed about 10 years ago and since then it has been thoroughly proved in practice. This paper reports on this method and describes the special seam welding machines used.

Principle of Foil Seam Welding

Figure 1 shows the fundamental arrangement with this welding process. The sheet metal panels I and II come into contact at their cut edges in the butt joint *SF*. For theoretical purposes the thickness of the sheet metal panel may be considered to be divided into a middle zone *MZ* and two border zones *RZ*. Between the electrode wheels R_1 and R_2 there are two foils F_1 and F_2 lying centrally on the butt joint of the two panels.

Concentration of welding current

For theoretical considerations alone, the butt welding of the two panels may be considered as starting from the middle zones of *both* sheets, where a welded nugget is formed from which the welding then can grow up to the surface. The current flowing from the two electrode wheels through the piece to be welded would indeed produce a heat centre at any contact area between the wheels, but because the foil inserted between the sheets and the electrode wheels creates an elevation, the current is concentrated precisely at this point. Although the foil is only 0·2 mm (0·008 in.) thick this is enough to attain the desired effect, and the current is concentrated within the small width of the foil 4 mm (0·16 in.) Thus, when the upper and lower foils are placed centrally on the contact line of the two panels the total welding current flows and consequently heats only the material next to the butt joint *SF*.

The central placing of the foils on the seam naturally cannot be done at will by hand but must be performed mechanically, because any lateral displacement would result in leading the current through only one sheet metal panel and only this one would be heated. Therefore, a guiding device is provided, which reaches almost to the contact point of the electrode wheels with the panels (*see* Fig. 2). This precise

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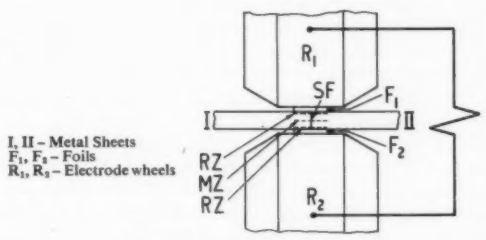
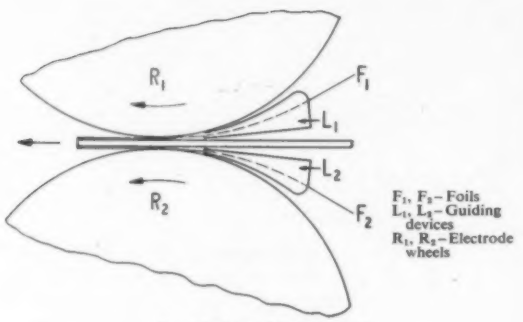


1—*Principle of foil seam welding*



2—*Method of guiding foils*

positioning is important, for the heating of the foil in front of the welding zone would otherwise tend to produce lateral distortion.

Heating of border zones

A further important problem is to obtain sufficient heating of the sheets in the border zones as well as in the central contact area. Indeed the foils result in additional electrical contact resistance for the passage of current, and so increased heat generation, but on the other hand the water-cooled electrode wheels withdraw considerable quantities of heat from the welding area. This is desirable with lap welding because the electrode wheels cool the outer surfaces of the overlapped pieces and so reduce distortion. With foil-seam welding, however, different conditions prevail because the panels must be heated through their whole thickness if complete fusion is to be obtained. The foils thus restrict the withdrawal of heat through the electrode wheels. The thicker the foil, the more it protects the welding zone against too much heat transfer and the greater is the heat available to the outer zones of the weld area and on the inner sides of the foils. If a specially thin foil is being used, say about 0·1 mm (0·004 in.), it is nearly impossible to effect a weld in the sheet metal panels up to the border zones of their contact surfaces, and the foils do not weld to the panels. Even under the most favourable conditions it is always difficult to obtain a thoroughly homogeneous weld between foil and sheet, which is more like a pressure weld without preheating. Yet, as a too thick foil, 0·5 mm (0·020 in.) thick or more, will bring about an undesired thickening of the welded seam, it is necessary to compromise. Extensive tests and experience over many years with a great number of foil seam welding machines have shown that the best conditions on the whole are obtained with a foil thickness of 0·2 mm (0·008 in.) Specially dimensioned foils may of course be preferred in particular cases.

This problem of heating the pieces to be welded over the whole area of the contact edges is specially important because the extent of the welded zone is hidden by the overlying foils. An incomplete weld will give no essential decrease of strength for tensile stresses, but would reduce resistance to bending stresses. The problem cannot be readily solved by increasing the welding current, for this would result in overheating at the outside of the foil and also sticking between the electrode wheels and the foil. If the chosen values for the welding power, welding pressure, welding speed and thickness of the foil are not in the right proportions small pores, visible by X-ray examination, appear in the middle zone of the area to be welded. These emanate either from gas formations or from volume changes during the solidification of the molten pool. Such minor porosity has no marked influence on the strength of the seam nor is it likely to result in fracture of the seam, for it never reaches the border zones. But, as already stated, porosity can be avoided by the correct choice of the welding variables.

The most suitable conditions for all these questions of the heat distribution over the total range of the area to be welded, can be provided by:

(i) Regulation of the welding current in the form of short and differently timed impulses of high amperage
(ii) Correct choice of welding speed and welding pressure.

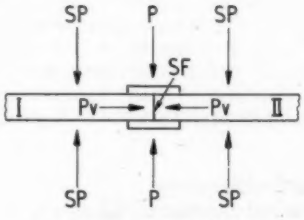
The increased transition resistance provided by the foils has only a secondary effect on heat generation and, therefore, on the welding in the border zones; and extensive tests with foil surfaces having an artificially increased transition resistance have shown no appreciable gain.

Welding pressure

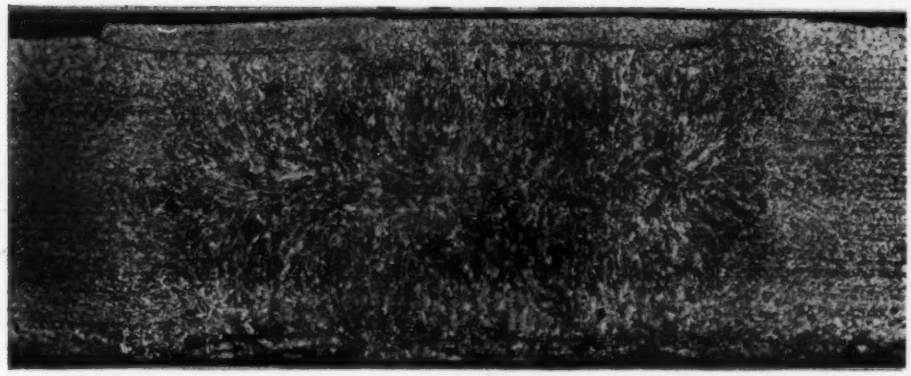
All resistance welding methods presuppose the application of a considerable mechanical pressure for squeezing the material of both parts to be joined after it has become plastic. This welding pressure has to be applied normally to the surfaces to be welded, so that with the peculiar conditions in foil seam welding in regard to the direction of the pressure transmitted from the electrode wheels, it would seem that satisfactory welding would be impossible.

Figure 3 shows that the pressure *P* exerted by the electrode wheels is applied exactly parallel to the welding surface *SF* and not normally to it.

A pressure applied at right angles to the welding surface may be attained indirectly by tightly clamping the two sheet metal panels onto a support, so that the clamping pressure *SP* is considerably larger than the pressure *P* exerted by the electrode wheels. In this way the two sheets, before being welded together, become a rigid although not homogeneous component. The material of the two sheets that lies between the two foils is heated as desired by the passage of current from one electrode wheel to the other, thereby creating an expansion that, with the sheets in the clamped position, has an upsetting effect *PV*. The total material heated for welding is therefore pressed together from all four sides by the pressure *P* and *PV*. This provides the pressure conditions which are indispensable for resistance welding. The correct clamping of the sheets has to be done against a rigid



3—*Pressure distribution*



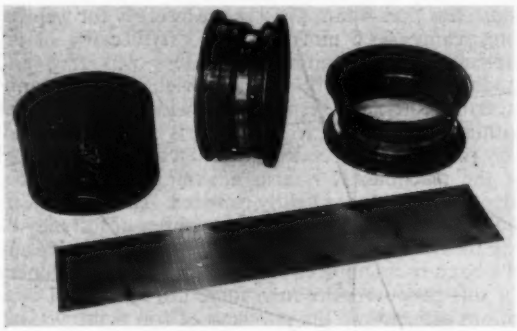
190 D.P.N. Sheet I | 210 D.P.N. Centre of seam | 190 D.P.N. Sheet II

4—*Macrosection of foil seam weld* ×40

supporting surface, for large expansion forces are involved especially with longer weld seams. Some help may be given by using tack welding. This abutted tacking is not simple, but it can be done with a spot welder having specially formed electrodes. Gas welding is also possible but with this method the tacked spots have to be dressed flush and cleaned for the subsequent seam welding.

The thicker the sheet metals, the larger become the expansion forces emanating from the welding heat. In such cases it may be advantageous to tack weld as well as to use the upper and lower foils, although considerable care is needed. Too much welding heat causes the surface of the foil at the tacked spots to become scaled and so creates a danger of burning in subsequent seam welding if the tacked spot has not been previously cleaned. The spacing of the tack spots must not be too great, for otherwise, during the final seam welding, the foil may expand between the spots and fall over on itself.

Fundamental research work has proved that the necessary pressure, correct current, and the required welding heat can be met excellently and adequately.



5—*Foil seam parts formed after welding*

Grain structure

Figure 4 shows a polished and etched section of a butt seam weld between two sheet metal panels 2·0 mm (0·08 in.) thick. The dark coloured welded zone between the upper and lower foils may be clearly discerned but there is no sign of the original, central seam which has been completely fused.

The grain structure clearly shows the thermal influences. The real welded zone was influenced to a great extent by relatively sudden cooling from the water-cooled electrode wheels and has a hardness of 210 D.P.N. On both sides adjacent to this zone there is a very small refined area beside which the grain structure is unchanged from the 'as-received' condition; the hardness in these areas is 190 D.P.N. The foils are welded together with the sheet metal panels lying thereunder and above on various areas.

Practical Experience of Foil Seam Welding

The practical man is interested in the data attainable and attained in practice and efficient operation. The following details are based on extensive experience gained over many years with a great number of butt seam welding machines.

Quality of the foil seam

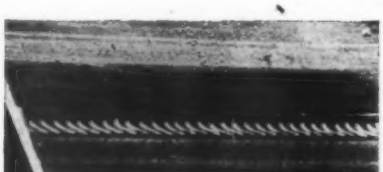
Satisfactory applications are the best demonstration of the real quality of the welding process used. Foil seam welding complies with the following requirements.

It is possible without difficulty to obtain a liquid- and air-tight weld with this process. Tube caps

welded by transverse foil seams have been tested for air-tightness to a pressure of 200 atm. The attainable liquid-tightness is again proved by the preferred use of this process for making the seams in motorcycle petrol tanks.

The welded seam is capable of being deformed to a great extent. Erichsen ball thrust tests result in deep-draw values 90–95% of those for the unwelded material. The fact that the seam is capable of good deformation allows rectangular deformations to be made with a small bending radius across and inclined to the seam, whether this is done on presses or with burnishing lathes (*see* Fig. 5), and the welding seam will also stand deformations in the longitudinal direction. In this connection a foil butt seam welding machine has been used successfully for making radiators from sheet metal panels; when punching out and deforming the radiator parts the butt seam is sometimes deformed over nearly its whole length at about 180°. And in the subsequent hydraulic pressure test all seams deformed in this way have proved to be completely tight.

Figure 6 shows the appearance of a foil butt seam. The heated zone, discernible by the discoloration, has



6—Surface of foil seam weld

a total width of only 15–20 mm (0·6–0·8 in.), which explains why the joints welded according to this process have no troublesome distortion.

Everyone who has experienced the cumbersome and costly expense of straightening out thermal distortions will be able to appreciate the special advantage of obtaining a foil butt seam free of this trouble.

A tensile test on a foil seam leads to a break in the refined zone or in the base material but never in the welded zone itself. In this connection it is interesting to learn about the results of tests which have been made at the Eidgenössische Materialprüfungs- und Versuchsanstalt, Zurich, in the form of tensile fatigue tests in a pulsator equipment operating at 10,000 load cycles per minute.

The foil butt seam welds were made in deep-drawing steel sheet panels (Armco) with a thickness of 2·3 mm (0·092 in.) The loss in strength, after more than 2×10^6 cycles at 2 tons load, was hardly discernible against the strength of the unwelded material as delivered from the rolling mill.

Besides the absence of distortion a further advantage of foil butt seam welding is that generally no refinishing of the seam is necessary, because the thickening of the joint amounts to only 0·10–0·15 mm (0·004–0·006 in.) when using top and bottom foils of 0·2 mm (0·008 in.) thickness each. In such cases where, for reasons of appearance or the need for subsequent refining and polishing of the surface, this small thickening has to be removed, a light grinding will suffice.

Preparation of material

The sheet metal edges to be butt welded must be positioned evenly in *one* plane. It is not possible, for example, to butt weld a sheet metal panel of 3 mm (0·12 in.) thickness to one 1 mm (0·04 in.) thick. An unsatisfactory welding result is also obtained if there is considerable distortion at the sheared edges of the sheets.

The surfaces of the pieces to be welded must be clean in the areas traversed by the electrode wheels, *i.e.* there must be no oxide- or scale-films present, as for any standard resistance welding process. The gap between the sheet edges must not be larger than approx. 0·3 mm (0·012 in.) Experience has shown that this requirement can be met with the use of properly working shears; mill finished edges are also usually satisfactory. The presence of light films of oil is not harmful.

Foil material

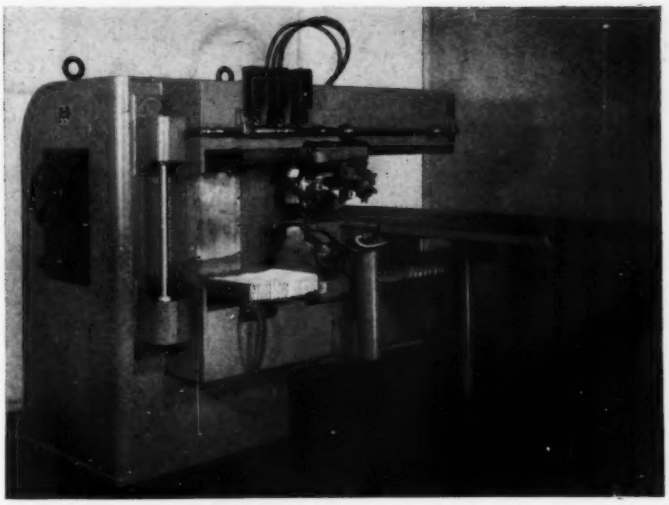
A bright, low-carbon, soft steel tape has proved to be an excellent material for foil for all standard steel sheet qualities. Only when specially alloyed sheet metals are to be butt welded, *e.g.* 18/8 stainless steel, is it necessary to use a foil of exactly the same material. The width of the foils is uniformly 4 mm (0·16 in.), but the thickness may vary between 0·2 and 0·5 mm (0·008 and 0·020 in.); in most applications a thickness of 0·2 mm (0·008 in.) is preferred. As already mentioned thinner foils give unsatisfactory welding results. Also it has been found inadvisable to choose a foil width less than 4 mm (0·16 in.), especially for welding long seams (4000 mm) (about 13 ft) because of the difficulty of maintaining accurate positioning and guiding of foils in the welding machine. The manufacturing tolerances, especially in width, must be kept within narrow limits, so that there is only a very small play in the guiding devices attached at the roller head of the machine. It is also advantageous if the cut edges of the foils are lightly rounded. All these aspects indicate that although suitable qualities of foil may be obtained easily the manufacture should be done only in a band rolling mill equipped with special machinery for this purpose. Although there are no special conditions attached to the purchase of foil seam welding machines it is the usual practice of all customers, within the country as well as abroad, to procure their continuous requirements for foils centrally with the supplier of these welding machines. This makes it possible to manufacture the foils in large quantities and, therefore, at low cost; at the same time there is always sufficient stock available. The foils are delivered, reeled on coils containing 1 kg each; equivalent to a length of approx. 160 m (525 ft). The mounting or changing of reeled foils can be performed without trouble at the respective holding device of the seam welder. The price of reeled foil has remained unchanged for some years at approx. DM 0·05 per metre (0·3*d*/ft). To save foil material in many applications where strength requirements are low only one foil is being used, and this is applied on the outer side of the piece to be welded.

The fact that foils are purchased from a central point makes it possible to obtain conveniently a survey about the actual application of this welding process. Already in the year 1958 seams of a total length of one million metres (about 3·3 million feet) had been welded by means of foil. The process has formed more and more new applications and the consumption of foil during 1960 amounted almost to 1·5 million metres (about 5 million feet).

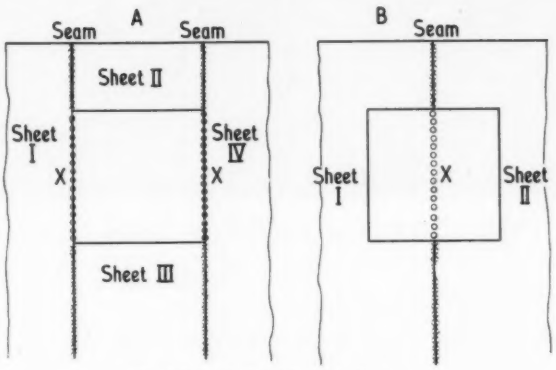
Welding speeds

The attainable welding speeds range from 2·5 m/min (about 8·2 ft/min) to 0·8 m/min (about 2·6 ft/min); this is for sheet thicknesses from 0·8 to 3·5 mm (0·03 to 0·14 in.) For smaller sheet thicknesses it is recommended to use a mash welding method whereby extremely small overlaps of only about 1 mm (0·04 in.) produce a highly satisfactory joint. For thicknesses exceeding 3·5 mm (0·14 in.) other seam welding processes should be applied, preferably in the field of fusion welding.

A consideration of the welding speeds attainable with foil butt seam welding leads as a matter of course to a comparison with standard lap seam welding. With the former process the current must be ignitron controlled. This limits the maximum welding speed to about 2·5 m/min (about 8·2 ft/min). The same conditions and speeds apply to the lap seam welding when a high-quality seam is required. But in this process it is sometimes possible to dispense with the use of ignitron panels, so that higher welding speeds are possible. The energy requirement for foil seam welding is somewhat higher in the lower range of the weldable sheet metal thicknesses, *i.e.* from 0·8 to approx. 1·5 mm (0·03 to approx. 0·06 in.) than for lap seam welding. With thicknesses from 1·5 to 3·5 mm (0·06 to 0·14 in.) the comparative figures change very advantageously in favour of foil seam welding; for example, for the seam welding of sheets 2·5 mm (0·10 in.) thick having a welding seam length of 4000 mm (about 13 ft) with large portal seam welding machines, only an energy of approx. 135 kVA is needed.



7—Model NPH foil seam welder



8—Method of welding windows

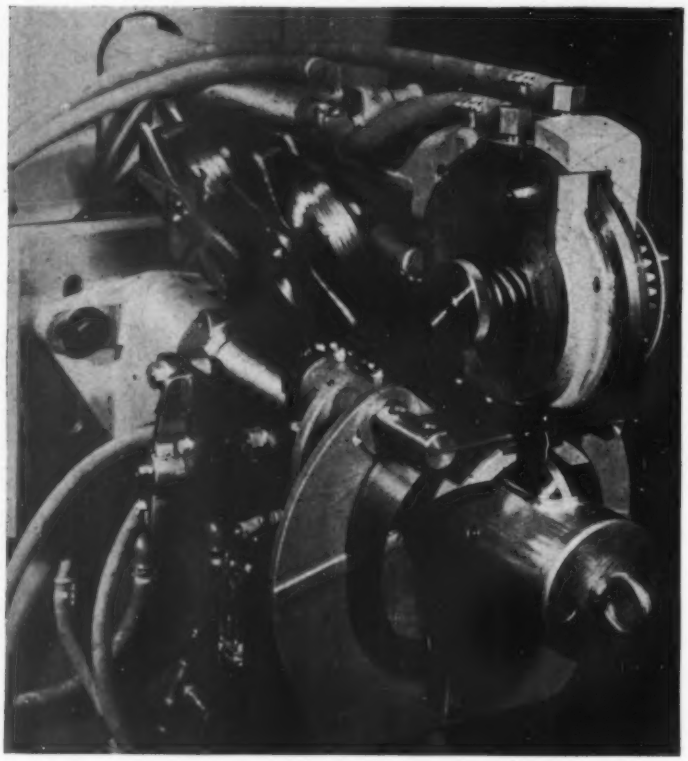
Machines for Various Applications

Many advantages of this process have become apparent in the course of its development in some main fields of application. These may be grouped as follows:

(*a*) Applications to save material
(*b*) Applications for subsequent enamelling or galvanizing, or for chromium-plating after seam welding
(*c*) Applications for long and very long seams where absence of distortion is essential.

Material economy

This welding process has been used in different ways to save material. Some firms utilize all their waste sheet metal parts by joining them together by butt seam welding and then using the larger sheets for the covering of equipment, machines and so on. Other plants, where for example stock sheets of the right size cannot be obtained, are realizing quite considerable savings of material and cost by adding rectangular and various dimensioned sheet sections to standard sheet sizes by this welding method. For such applications the type of machine shown in Fig. 7 has proved to be very useful. There the work table of the machine, equipped with magnetic plates, serves for the simple and quick clamping of the sheets to be joined. Above and below their contact lines electrode wheel heads are moved simultaneously. At the end of each completed seam the welding current is switched off, but the movement of the electrode wheel heads continues, and the separation of the unwelded foil between the sheets and the foil guiding device together with the reeled foil is performed completely automatically by a current impulse. This separation of foils right away behind the welding action, is timed in such manner that there always remains a sufficient piece of foil below the electrode wheel to serve as a start for the next seam weld. The machine, therefore, is automatically prepared for the next welding operation and it only requires the operator to take out the welded panels and locate the new sheets in the correct position. This is facilitated by stop gauges and the subsequent magnetic clamping. Such machines are also used among others in the automobile industry, either for the manufacture of unformed sheet sizes which agree



9—*Model N1 6·5St foil seam welder for headlamp rings*

exactly with the precut sizes for the forming tools or even for the seam welding of already formed car body parts. In such cases these are, of course, single-purpose machines which need, for their economic usefulness and amortization, relatively large quantities of production. With welding machines as that shown in Fig. 7 it is possible to produce panels with rectangular cut outs—for instance window cut outs of elevator doors—and this without leaving any scrap. Thus, for instance (Fig. 8), an elevator door would be welded either from four sheets according to procedure *A* or from two sheets according to procedure *B*.

The electrode wheel heads, which are moved forth and back on the current conducting rails of the upper and lower arms of the welding machine, run with increased speed over the window openings *x* which in both operational procedures do not have to be welded. This extremely efficient working procedure is applied also when welding together the wide walls of railway coaches, which contain many window openings.

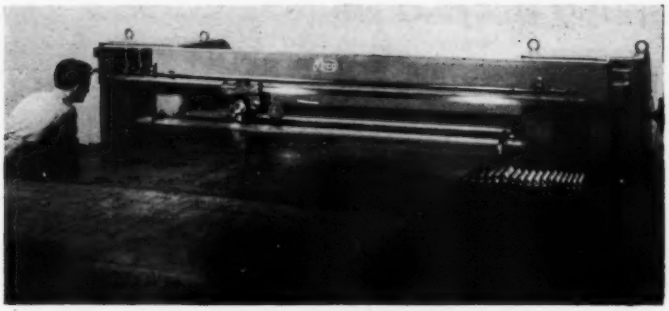
A smaller special machine (Fig. 9) has served for years in the production of rings for automobile headlamps from sheet metal strip; in this example any waste of sheet metal is completely avoided. According to conventional production headlamp rings are cut from a sheet corresponding in size to a full ring plate and are subsequently formed into shape.

Foil seam welding makes it possible, however, to use initially a sheet metal strip from which a ring is welded by a short seam and is subsequently partly formed up to 180° by means of a bending tool; there is thus no need for cutting tools.

Subsequent surface treatment

Seam welded sheet metal parts which have to be enamelled on the inside or outside must not have a lap or unevenness on the welded seam. Instead of the autogenous or arc welding formerly used, for example

10—*Model NLr 30St foil seam welder*



11—*Model NP 4000St cross-bar foil seam welder for a maximum seam length of 4000 mm (13 ft)*

in such applications as all kinds of household machines and utensils, especially the inner drums of washing machines, the foil seam welding process can be used with advantage. Also formed parts which after seam welding are either lustre lacquered or chromium plated may be foil seam welded, as is shown in Figs. 5 and 10.

The forming of the water container and the conical washing machine shown in Fig. 5 was done on a burnishing lathe. The work samples in Fig. 10 show motor-scooter front parts; foil seam welding simplifies their production very considerably because the production of a single drawing piece would cause very high tool expenses.

The welding together of two preformed halves of tanks for motorcycles is a typical and frequent application for formed sheet metal parts whose surfaces are to be treated after the welding, for instance chromium-plated. Such finishing presupposes the absolute absence of distortion of the welded seam.

Long seams

In the production of long welded seams in thin sheet there is always the danger of distortion caused by the very considerable heat carried into the sheets from the seam. Every plant engineer knows how difficult it is to remove this distortion once it has occurred. From these considerations the type of crossbar or portal foil seam welding machine shown in Fig. 11 has been developed for the manufacture of railway coaches and for the construction of large sized vehicle bodies (buses). In the course of time these machines have been delivered to almost all industrial countries in the world.

The main dimensions of the machine are: length of the welded seam 4000 mm (13 ft), total width of machine 6500 mm (21 ft), weight 5·5 metric tons. The various advantages of such crossbar machines are so important and they are so efficient that in many cases they have been operating continuously in two shifts, and some large industrial plants have been supplied with two machines of this type for their sheet metal workshops.

The roofs of railway coaches of about 20 m length and up to 4 m (13 ft) wide are manufactured with these machines by welding together as many sheets 4 m (13 ft) wide as are desired. An especially efficient production is attained when the *total* length of the roof of about 20 m (65 ft) is welded together from eight panels of the dimension 4000 × 2500 mm (13 × 8 ft) without interruption and is rolled up on the rear side of the welding machine on a movable cylindrical equipment. This rolled-up roof covering of 20 × 4 m (65 × 13 ft) is transported by crane to the coach assembly area and is placed in position by rolling it off onto the frame construction of the roof.

The clamping of the sheet panels to be welded is again done with large magnetic plates, so that with these unusually long welding seams no warping or distortion arises. The outside of the welding seam has a tempering discoloration 20 mm (0·8 in.) wide; this uniform band over the total length demonstrates that there has been the same heating at each point of the seam. This is attained by phase-shift heat control of the welding current which operates automatically as the inductive reactance varies with distance across the seam.

The side walls of railway coaches, already referred to, are also produced in such portal machines. Many fully automatically controlled working procedures with such machines—among them the cutting or burning off of foil shortly behind the end of the seam, and a central lubricating system for all parts gliding against each other and at the same time conducting current—make it possible for these unusually large welding machines to be operated by untrained personnel.

Conclusions

By the use of the correct procedures and with a knowledge of the applications of the process, foil seam welding has been shown to be successful. The numerous advantages of such seams—no distortion or warping of the sheet metal, a seam that is clean and has practically no thickening, high strength and good forming qualities, high welding speeds and a relatively low demand for welding power—quite outweigh the small additional cost of this process; *i.e.* the additional cost of foil and the special equipment of the welding machines. Foil seam welding is not a substitute for lap welding, but when butt seam welding is specified this process, operating with foil in the range of sheet thicknesses 0·8–3·5 mm (0·03–0·14 in.), may in many cases be superior to other welding processes. This applies especially when the seam is to be surface treated after welding or when very long seams are involved. Foil seam welding is able to fill the gap existing between the border fields of resistance lap welding and the various processes of autogenous and electric arc welding.

SPRING MEETING 1961

Auto-Pneumatic Metal Spraying Machines

Increasing use is being made of pneumatic power systems for mechanized metal spraying. The paper presents the requirements of equipment for this purpose and gives details of the auto-pneumatic control system that has been developed for special applications.

By W. E. Stanton

PNEUMATIC power systems are being used to an increasing extent in the operation of mechanized metal spraying installations. This is not surprising, since compressed air is an essential commodity whenever the spraying process is used. Modern pneumatic equipment is not unduly affected by the dusty atmospheres commonly associated with metal spraying, and it has proved far more reliable than electrical apparatus. This is no doubt because pneumatic systems are pressurized under working conditions, and internal surfaces are all constantly lubricated. Further advantages offered by pneumatic equipment are compactness, flexibility, and that highly specialized knowledge is not required when servicing becomes necessary.

The increased use of such equipment was instrumental in promoting the development of automatic methods for controlling complex pneumatic systems, and one of the methods evolved has been successfully applied to a metal-spraying machine which was specially designed for zinc coating the prefabricated parts of a large suspension bridge now under construction.

The auto-control system allows the use of mechanisms which provide greater flexibility of nozzle movements than has previously been possible, with the result that no readjustment of the machine is necessary when alternately applying coatings to workpieces as diverse in shape as welded box sections and built-up fabrications.

Scope and General Principles of Existing Machine

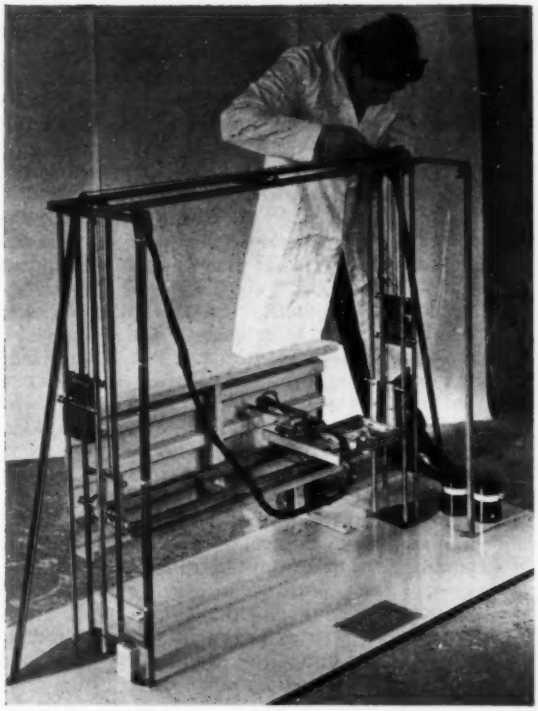
The machine is capable of coating surfaces 16 ft long by 18 ft high in a single spraying sequence. All workpieces are presented so that the surface to be coated is vertical and parallel with the front face of the spraying machine; workpieces of greater length than the machine are presented to the spraying face in successive increments of 16 ft. Shorter pieces can also be accommodated without wasteful loss of overspray by a simple adjustment of the pistol traversing mechanism.

Manuscript received 6th February 1961.
Mr. Stanton is with Metallisation Ltd., Dudley, Worcs.

By comparison with many existing spraying machines the required coverage (sq.ft/hr) is quite small, and is easily accomplished by two nozzles, each spraying $\frac{3}{16}$ in. dia. wire. In operation the twin-nozzle pistol assembly is caused to scan the surface presented to the machine, commencing at the lower edge of the workpiece and proceeding through a succession of horizontal traverses, to the upper edge. At each reversal of direction the position of the nozzles in relation to the workpiece is automatically adjusted, so that the spray streams are directed onto an adjoining path. The coating is therefore applied in a succession of parallel stripes in similar manner to the ploughing of a field. In the treatment of perfectly flat surfaces, re-direction of the nozzles is achieved by hoisting the whole traversing mechanism carrying the pistols by an amount equal to the width of one combined spray. However, many of the surfaces are of irregular profile, and in such cases re-direction of the nozzles becomes more complex.

The most difficult profile is presented by the underside of roadway deck plates, which have inverted reinforcement channels welded along their full length, in addition to longitudinal skirts welded to both edges at right angles to the major surface. A scale model of the machine has proved to be invaluable in solving initial design problems (Fig. 1). Re-direction of the nozzles for treatment of the upper and lower skirts involves vertical rotation through 180°, since the spray streams must be directed vertically downwards onto the inner surface of the lower skirt, and vertically upwards for treatment of the upper skirt. The channel walls are inclined outwards from the major surface so that the profile between adjacent channels takes the form of a trough 8 in. deep and 13 in. wide at the base, opening to 17 in. wide at the mouth.

At each traverse of the twin nozzles a coating 8 in. wide is applied; thus, four traverses are sufficient for complete coverage of each trough provided that the nozzles are suitably positioned. This is achieved by pivoting them about a point midway between the channels, and at a distance of 11 in. from the base line. They are free to rotate in a vertical plane, but provision is included for the pivot to be locked at positions of 50° and 15° above and below horizontal. A further lock is provided to secure the nozzles in the horizontal



1—*Scale model of auto-pneumatic metal spraying machine for application to bridge deck plates*

position for the purpose of coating vertical surfaces. Between the coating of each trough, one traverse is required for treatment of the outer face of the channel web. This demands a double movement of the nozzles, consisting of a vertical hoist of 13½ in., accompanied by a horizontal retraction of 8 in. Both the hoist register and horizontal motion are powered by separate air cylinders, whilst the hoist motor is controlled by a pressure switch.

Further pneumatic mechanisms are provided to complete all movements necessary for re-directing the nozzles to meet the requirements of all types of workpieces for which mechanized spraying is specified. In total, twelve separate pneumatic systems are built into the spraying machine, all of which are automatically controlled, either individually or collectively, in any given sequence from a remote station.

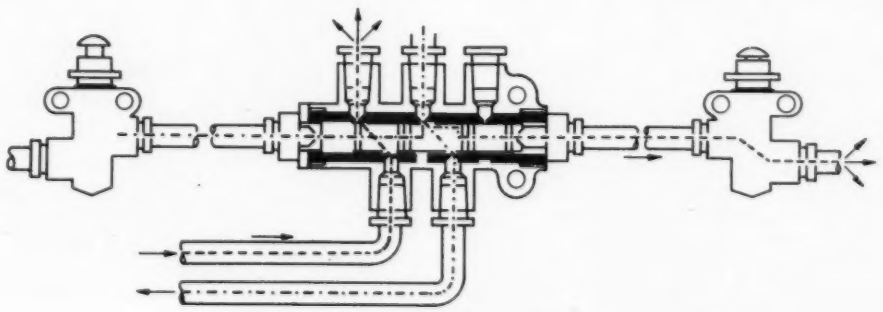
Auto-Pneumatic Control System

The principle of the automatic control depends upon the restriction of a small bleed of compressed air, which is allowed to escape from certain types of pressure release valves. In its simplest form a pressure release valve consists of a housing carrying an inlet, an outlet and a cylinder exhaust port (Fig. 2). A cylindrical valve member or piston is free to slide lengthwise in the housing, and is drilled in such a manner that a small amount of air flows from the inlet port to separate cavities at each end of the housing. When air is allowed to escape from only one of the cavities the pressure of air in the other is sufficient to force the valve piston to the opposite end of the housing. When the process is reversed, *i.e.*, the open cavity is closed and *vice versa*, the valve piston returns to its former position.

Conversion from manual to automatic operation of this type of valve is accomplished by the provision of a perforated sliding member, which allows air to escape first from one cavity and then the other. The sliding member may take the form of a perforated strip or belt, to which motion is applied either continuously or intermittently. When continuous steady motion is applied the spacing of the perforations determines the intervals of time the valve is held in either the open or closed position.

Three-way valves as described are suitable for feeding single-acting cylinders, but four-way valves capable of feeding double-acting cylinders operate on the same principle, and can be controlled automatically in similar fashion. Spring return valves are also used, in which case only one pressure cavity is controlled by the sliding member. When air from the pressure cavity escapes to atmosphere a compression spring forces the valve piston along the housing towards the cavity, while restriction of the escaping air allows sufficient pressure to build up to force the valve piston away from the cavity and compress the return spring.

It will be clear that a sliding strip less than 1 in. wide carrying two rows of perforations is sufficient to control one valve. If, however, the pressure cavities of a number of valves are connected to a closely packed row of ports, a perforated strip of suitable width to

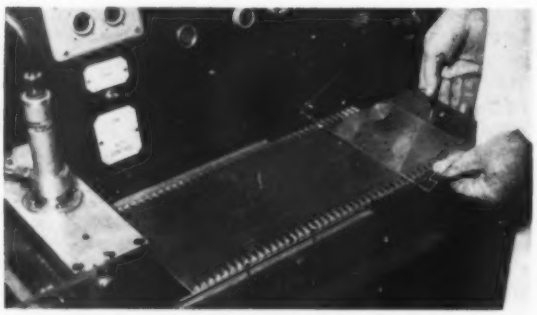


2—*Simple functional use of Maxam pressure-release operated valve*

cover them all will simultaneously control the whole series of valves. Furthermore, no matter how often the perforated strip is passed over the pressure release ports, exactly the same sequence of valve settings will be repeated. An almost unlimited and entirely different set of sequences may thus be produced by means of suitably perforated control strips.

Control strips

Control strips for the existing machine are formed from $\frac{3}{16}$ in. thick brass plates, $8\frac{1}{2}$ in. wide and 15–30 in. long, having serrations cut along both edges of the top face (Fig. 3). The serrations are provided to engage with a pair of ratchet pawls, which by means of



3—*Control strip being positioned*

a small air cylinder are rocked backwards and forwards so that the control strip is propelled intermittently across the pressure release ports. Every forward movement is synchronized with a reversal of the pistol carrier. This is achieved by linking the pilot valve feeding the ratchet cylinder with the horizontal traversing stops. At each successive forward movement pressure release ports are exposed, which energize the mechanisms necessary to produce the pistol movements required for deposition onto the subsequent spray path. The auto-pneumatic control unit forms the centre piece of a remote panel (Fig. 4).

In addition to auto control, provision is made for manual operation of the simpler movements by means of hand valves, which are inter-connected with the pressure release ports. This refinement allows for the mechanized treatment of many different types of workpiece that occur only once or twice in the bridge structure, and therefore do not justify the manufacture of control strips. Manual controls are limited to simple lifts and retraction through 8 in., together with rotation and locking at 50° above and below horizontal. Further hand controls would be superfluous, since one operator could not cope simultaneously with more.

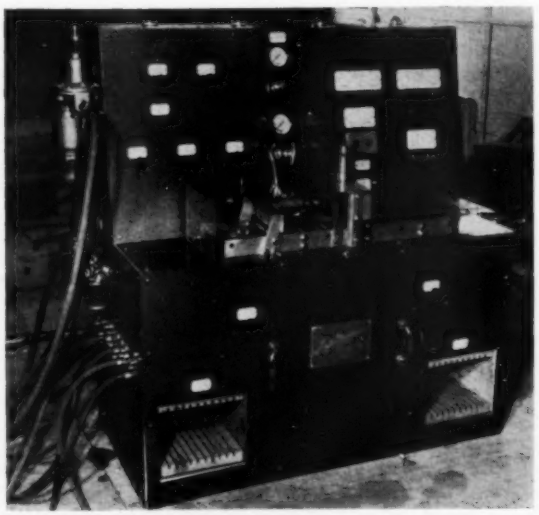
Nozzle re-directing mechanisms

It is pertinent, perhaps, to mention the various mechanisms by which movement and locking of the pistols in the various positions are obtained.

As previously stated the basic nozzle movement consists of a succession of horizontal traverses alternately to left and right. This movement is obtained by means of a motorized four-wheel carriage or bogie running between twin tracks which are suspended parallel to the front face of the machine. A second pair of tracks extending from front to back of the bogie carry a similar wheeled bogie. Transverse horizontal motion is applied to this bogie by two air cylinders, the larger cylinder, 19 in. long, being secured to the lower bogie, and the smaller one, 8 in. long, to the transverse bogie. The cylinders lie horizontally opposed, with their piston rods connected. When both piston rods are fully extended, the nozzles are situated at the normal spraying position for the treatment of flat surfaces. But from this position they may be retracted by amounts of 8, 19, or 27 in. by suitably energizing the two cylinders.

A secondary automatic control applied to these cylinders ensures that the pistols are instantly retracted should they be in danger of fouling any obstruction on the workpiece. This movement is initiated by slight pressure of the obstructing object against hinged panels at each side of the pistols. The panels are mechanically linked with simple spring-loaded valves, which are connected to the pressure cavities of the master valves feeding the two cylinders. The spring-loaded valves allow an escape of air in the same way as the auto control strip.

Extending forwards from the transverse bogie, two arms carry pivot bearings at their extremities to support the spraying nozzles (Fig. 5). Rotation through 180° is imparted to the nozzles by a double-acting cylinder connected to a cranked shaft, which in turn is coupled by a chain and sprockets to the pivot shaft. One full stroke of the cylinder piston turns the nozzles through one half revolution but, to ensure that the crank does not approach dead centre, unequal sprockets are fitted so that it rotates through only one third revolution. The cranked arms may be held at various intermediate angles by slotted cams securely fitted to the shaft, and these engage with roller cam levers. A small air cylinder connected to each lever forces the lever roller on to the periphery of the cam. At the same time rotation is imparted to the cam by



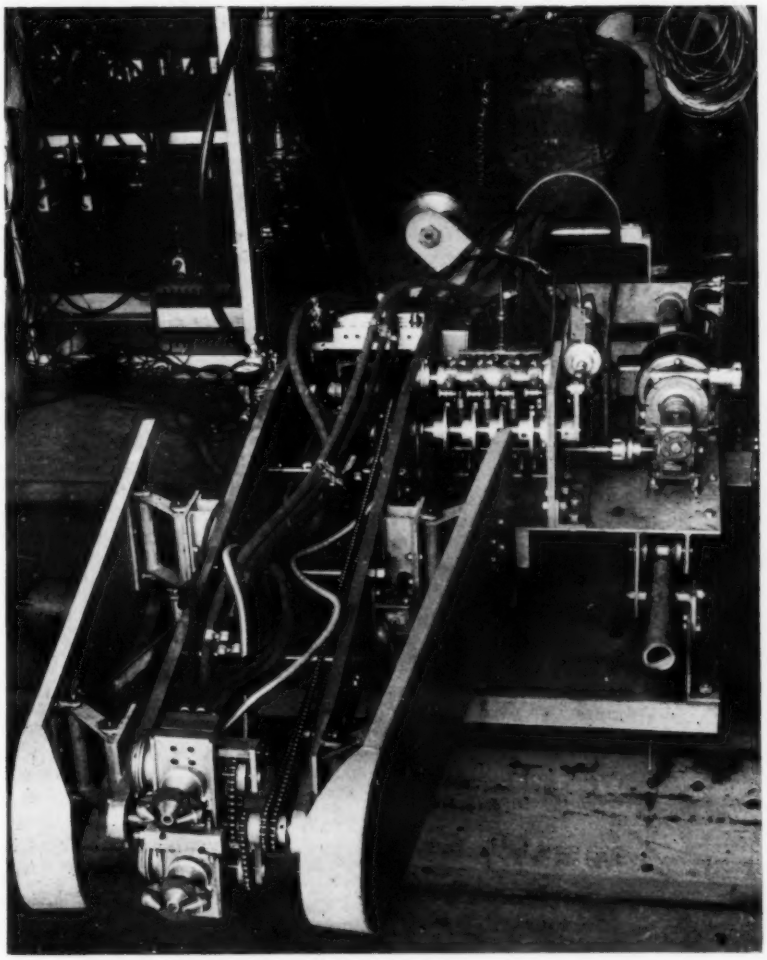
4—*Auto-pneumatic control unit*

the crank so that the rollers fall into the cam slots as they come into line—thus preventing further rotation. The positions of the cams when engaged with their associated roller levers determine the individual angles at which the nozzles may be held, and the angle required at any instance is obtained by energizing the rotation cylinder either forwards or backwards together with the appropriate cam cylinder.

Vertical movement is provided to raise the nozzles successively in increments of 8, 11, or 13½ in. Power for hoisting is provided by an electric motor, but the mechanism to determine the extent of each vertical movement depends upon three dry-plate clutches powered by pneumatic cylinders. The clutches are fixed to a common shaft, geared to the hoist drive, so that, with the exception of the friction plates, they are caused to rotate at a slow but proportionate speed when the hoist motor is running. Return springs normally hold the friction plates against a pre-set stop, but on supplying compressed air to the associated air cylinder, the plate also rotates to a position where an arm extending from it trips a limit switch, thus breaking the electrical circuit to the hoist motor. The amount of travel allowed by each clutch is determined by the angle of rotation between the pre-set stop and the point at which the limit switch is engaged. At the commencement of each hoisting cycle the motor circuit is closed by a pressure switch at the same instant that the required clutch cylinder is energized—both under the control of the control strip.

Incidental refinements

Difficulties are frequently experienced in maintaining a consistent reserve of free wire when spraying pistols are alternately travelling towards and away from the bulk wire supply. Motorized wire swifts overrun on the return movement, whilst swifts fitted with friction pads exert additional loads and promote unnecessary wear on the internal feed mechanism of the pistol. In the present case the difficulties were increased by the tortous path entailed in feeding the $\frac{3}{16}$ in. dia. wires from drums located outside the spraying machine. Initially the wires must pass vertically from the drums to a point high on the outside wall, then horizontally for some distance to gain access to the inside of the machine. From there they must drape towards the rear of the transverse bogie, taking a right-angled bend towards the nozzles. A



5—Twin nozzles carried on extended arms

6—Earlier repetition spraying machine

further complication arises in the constantly changing angle of approach at the rear of the nozzles owing to the 180° rotational movement.

The essential requirements to overcome the difficulties were determined at the design stage by experiments with models and full-sized rigs. The rollers mounted vertically above the drums, together with the first pair inside the machine, are coated with resilient rubber, and are powered at a surface speed of 30 ft/min —the fastest speed at which the wire is calculated to run. The remaining rollers mounted on the transverse bogie are plastic coated, apply a driving pressure to the wires, and are power driven at a surface speed 20% in excess of the positive feed-drive rollers, located immediately behind the nozzles. A certain amount of slip takes place at the plastic rollers, but the additional driving force applied counteracts the additional friction caused by flexible guide tubes, through which the wires continue their journey to the rear of the nozzles.

Push-button ignition for metal spraying pistols is not new but brief mention is perhaps permissible since the remote control method in this instance follows the pneumatic pattern. It was assumed that ignition should be incorporated in the auto control system and pneumatic means were adopted to provide simultaneously pilot jet gas and a high-frequency spark. In practice it became clear that the controls were best kept separate, since additional isolating hand valves were too easily left at the 'ON' or 'OFF' position at the wrong time. Occasions must arise when attention is necessary to either nozzles or mechanical equipment and under these circumstances ignition control by a separate spring-return push-button valve at the control panel proved to be the most foolproof arrangement.

Progress in mechanical metal spraying as opposed to other surface treatment processes has been relatively slow owing to the limited field of application covered by each installation. A prolonged flow of identical articles has been necessary to justify the capital expenditure, and in many cases the plant has become virtually worthless when production of the article for which the machine was designed has ceased. Nevertheless, mechanized spraying has shown rewards in uniformity of the product, tighter thickness control, savings in metal, gases and labour and greater productivity. An earlier repetition spraying machine is shown in Fig. 6. Synchronized air cylinders progressively raise and lower the pistol and position the box being treated. The auto-pneumatic control system offers flexibility giving a wider field to the user, together with more complete coverage of irregular articles and possibly greater savings in labour. To the machine designer auto-control in any form represents a contemporary weapon and a challenge to the imagination.

Conclusion

A great deal has been said about industrial automation in recent years with particular reference to electronic methods. Magnetic relays, capacitor inductance circuits, transistors, etc., have made phenomenal strides in this field but in whatever manner machines are controlled the mechanical engineering end, where the productive work is accomplished, is still the least dispensable. Mechanical methods of control are not outdated although some certainly need modification to meet present-day needs. It is interesting to recall that the first automatic device, credited to James Watt, still gives excellent service in controlling the speed of steam engines.

SPRING MEETING 1961

Mild Steel Electrodes for Contact Welding

The paper discusses the design and properties of mild steel electrodes for contact welding. Comparisons are made between non-contact and various designs of contact electrodes in respect of electrode and welding costs. Examples are given of applications and reductions in welding costs achieved with a contact metal powder electrode.

By J. W. Addie, B.SC., A.M.INST.W.

A WELDING process may be said to attract attention in direct proportion to its novelty. Though initial enthusiasm may be greater than warranted by the merit or scope of the process, eventually it finds its due place in the pattern of practice. Then another new process is announced and the sequence of events is repeated.

In this background, manual arc welding has continued as the major welding process for ferrous metals. New standards of quality, ease of use, and speed of deposition have been demanded and met. Consequently the newer processes have not easily displaced the ubiquitous welding operator, his welding set, and his electrodes.

What features then have been responsible for the uninterrupted acceptance of the manual arc process? The essential merit of the welding electrode is flexibility in design to meet the varied demands in industry. Quality was advanced decidedly by the introduction of the low-hydrogen electrode with its advantages for work of major importance. More recently, electrodes suitable for welding with the coating in contact with the workpiece have been gaining acceptance. These 'contact' electrodes satisfy the demands for ease of use and high deposition rate with equal or better quality compared with non-contact types.

Properties of Contact Electrodes

The primary requirement for contact welding is the formation of a cup at the tip of the electrode. This cup acts as a crucible from which the products of fusion are discharged through the arc into the molten pool. The depth of the cup is desirably greater than the largest globule to be transferred to the molten pool, since this arrangement will eliminate short circuits as soon as the cup is established. Conversely, the cup must be shallow enough to keep the arc voltage and therefore the arc force within practical limits.

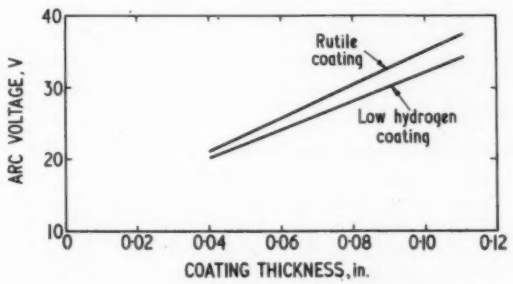
Arc voltage depends on: (i) thickness of coating; (ii) composition of coating; (iii) proportion of metal powder added to the coating; and (iv) current. Cup depth is affected by the thickness of coating and metal powder additions.

Coating composition and thickness

The two main types of coating applied to contact electrodes are:

(i) Rutile type, producing a viscous slag
(ii) Low-hydrogen type, producing a fluid slag.

Both types allow of contact operation at quite low thicknesses; with a 6 s.w.g. core for example, a thickness of 0·04 in. suffices. The upper limit of thickness is decided by the greatest volume of slag that can be tolerated and by the highest arc voltage at which welds free from undercut and other defects can be made. For 6 s.w.g. electrodes welded at 250 amp the effect of coating thickness on arc voltage is shown in Fig. 1, and upon cup depth in Fig. 2.



1—*Effect of coating thickness on arc voltage at 250 amp (6 s.w.g. electrodes)*

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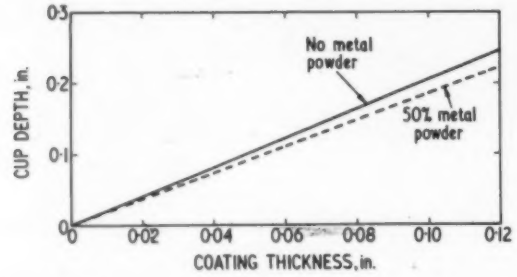
Mr. Addie is in the Heating and Welding Engineering Department of the Transformer Division of A.E.I. Ltd., Manchester.

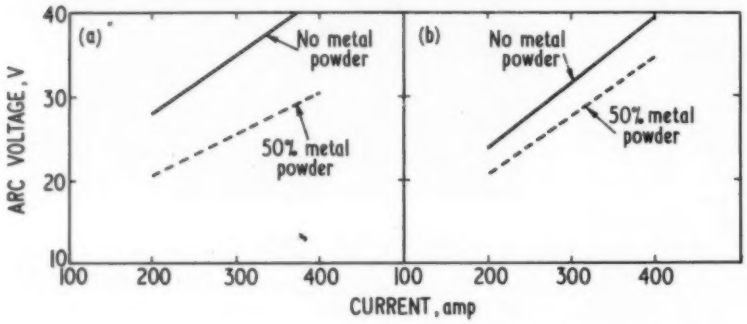


2—*Effect of coating thickness on cup depth (6 s.w.g. electrodes)*

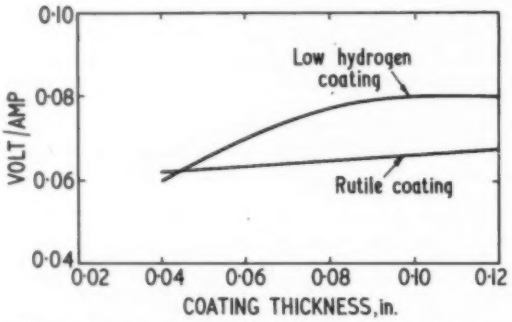
The effect of coating thickness on the slope of the curves for arc voltage against current is shown in Fig. 4. With the rutile type the rate of change of arc voltage with current V/A rises slightly with increase in coating thickness. In contrast, for the low-hydrogen type, V/A rises sharply from 0·06 to 0·08 and then levels off at 0·08.

Practical limits of arc voltage

Experience has shown that satisfactory operation requires the arc voltage to be in the range 23–35 V. The lower limit is fixed by the need to avoid short circuits, and the upper limit is designed to avoid excessive arc force which causes undercut.



3—*Volt/ampere characteristics for 6 s.w.g. electrodes*: (a) *0·08 in. thick rutile coating;* (b) *0·08 in. thick low-hydrogen coating*



4—*Effect of coating thickness on slope of volt/ampere curves*

Metal powder additions

Equal additions of metal powder to the rutile and the low-hydrogen type coatings have the same effect on their welding characteristics. Cup depth and arc voltage are reduced in proportion to the amount of powder added, and arc action becomes progressively quieter. At the same time, for a given coating thickness, the non-metal part of the coating, and therefore the slag, are of reduced volume. The upper limit of coating thickness is therefore extended by adding metal powder to the coating.

Volt/ampere characteristics

Comparisons of the volt/ampere characteristics are shown in Fig. 3 between electrodes with coatings containing no metal powder and the same electrodes with coatings containing 50% metal powder. The addition of metal powder has reduced the arc voltage for both the rutile and low-hydrogen types but to a greater extent with the rutile type.

Current

Since arc force is proportional to current, an increase in current results in faster flow of the molten metal from the pool to the weld bead, and the pool itself shows greater concavity. Consequently arc length and arc voltage are greater but cup depth appears to be independent of current and almost completely dependent upon coating thickness. Each coating variant has its own working range of current, the maximum limit being set by overheating of the electrode or by the onset of undercut.

Examples of coating design

As well as composition, the main variables in design are thickness and metal powder content. With no metal powder in the coating only a limited increase in thickness over non-contact types is practicable. Progressive increases of metal powder in the coating permit proportionate increases in thickness to maxima fixed by the volume of slag that can be controlled or by the maximum arc voltage that can be tolerated. Three examples for 6 s.w.g. electrodes are listed in Table I.

Table I

Coating thickness limits

	Example 1	*Example 2*	*Example 3*
Coating thickness, in.	0·055	0·075	0·08–0·10
Metal powder in coating, %	—	40	50
Current range, amp	200–260	225–305	250–350
Normal current, amp	230	265	300
Average arc voltage, V	25	27	29

Mechanical Properties of Contact Electrodes

Tensile

The tensile strength of all-weld-metal deposited by contact electrodes tends to be at the top end of the range for mild steel electrodes. As a result the 'as welded' elongation and reduction in area figures are at the lower end of the range, but a considerable improvement occurs after stress relief or storage of the weld. The effect of duration of stress relief at 650°C. is shown in Table II.

Table II

Effect of stress relief on mechanical properties

Time of Stress Relief at 650°C. hr	*Yield Strength, tons/sq.in.*	*Tensile Strength, tons/sq.in.*	*Elong. on 1·5 in., %*	*Red. in Area %*
—	31	35·5	24	38
2	31	35·5	31	64
10	29	34	33	66
65	27	32	37	70

For up to 10 hours stress relief the progressive improvement in properties is principally due to loss of hydrogen, and after 10 hours to spheroidization.

Hot-crack resistance

The higher tensile strength of contact type weld metal is, in some cases, due to a relatively high manganese content. The object of this feature of design is to impart a high degree of hot-crack resistance to the deposit by maintaining a high Mn/S ratio in the weld metal. This is of greater importance than with conventional electrodes since the weld sections deposited are generally smaller and their flatter shape gives smaller throat sizes.

Notch ductility

Energy-absorption/temperature characteristics of contact metal-powder type electrodes are similar to those of conventional types. The transition temperatures at 15 ft lb energy absorption on Charpy V-notch specimens from metal powder type electrodes, shown in Table III, illustrate this.

Table III

Notch ductility of metal powder electrode deposits

Coating	*Transition Temperature (15 ft lb)*
Rutile	−10° to −20°C.
Low-hydrogen	−30° to −40°C.

Table IV

Deposition rates for metal powder electrodes

	Example 1	*Example 2*
Coating thickness, in.	0·055	0·085
Metal powder in coating, %	—	45
Specific deposition rate per 100 amp, lb/hr	2·05	2·7
Normal current, amp	230	300
Deposition rate at normal current, lb/hr	4·7	8·1

Advantages of Contact Electrodes

Welding performance

With an appropriate slag, electrodes falling within the range of design given in the examples in Table I show distinct advantages over non-contact electrodes. These may be listed as follows:

(i) Wasteful convexity in fillets is avoided, since the weld contour is flat
(ii) The welding operation is easier using contact technique
(iii) In spite of a high level of arc force, undercut is absent and deslagging is easier
(iv) Spatter loss is lower, since short circuits by globules crossing the arc are eliminated.

Deposition rates

The metal powder electrodes show further advantages since, as the percentage of metal powder in the coating is raised, the maximum current that can be tolerated increases, and with it the rate at which the electrode fuses. As a result the rate at which metal can be deposited increases substantially, as shown in Table IV for 6 s.w.g. electrodes.

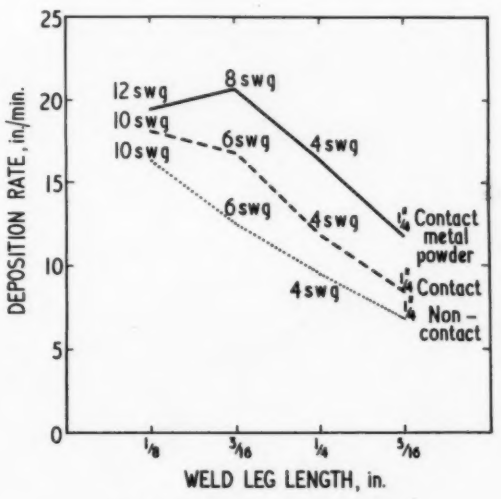
Reduction in welding time

Fillet welding data for the examples in Table IV are compared with those for a non-contact electrode in Fig. 5. The increased welding speeds for both the examples make possible substantial saving in welding time.

Welding technique

Contact electrodes can be used with contact or open-arc techniques. It is usual with the mild steel types to apply a contact technique in the first runs of fillets and butts and an open-arc technique for subsequent runs.

With a contact technique, travel speed should be 1½–2 times that for non-contact types to ensure that



5—Deposition rates for fillet welds

Table V

Comparative electrode costs

Electrode Type	*Coating Thickness, in.*	*Metal Powder, %*	*Electrode Cost per Length*	*Electrode Cost per Unit Weight of Deposit*
Non-contact	0·035	—	100	100
Contact 1	0·055	—	134	134
,, 2	0·075	40	186	137
,, 3	0·09	50	224	138

Table VI

Relative welding costs for single-run fillets

Electrode Type	*Coating Thickness, in.*	*Labour and Overhead Cost*	*Total Welding Cost*
Non-contact	0·035	100	100
Contact	0·055	77·5	85·5
Contact: metal powder	0·085	56	67·5

Table VII

Relative welding costs for prepared butts

Electrode Type	*Coating Thickness, in.*	*Labour and Overhead Cost*	*Total Welding Cost*
Non-contact	0·035	100	100
Contact	0·055	92·5	99
Contact metal powder	0·085	55·5	67·5

the close-following slag is kept under control. The effect of lengthening the arc is to increase the arc voltage and hence the energy driving the slag back. So with an open-arc technique travel speed should be up to $1\frac{1}{2}$ times the speed for non-contact types.

Welding Costs

Electrodes

Contact electrodes with their thicker coatings cost more than non-contact types. Costs for the examples in Table I compared with that of a typical non-contact type are shown in Table V. The relative costs per unit weight of deposit are also listed.

In view of the relatively higher electrode cost for contact and contact metal-powder electrodes, can a saving be effected in welding costs?

Fillet welding

Estimates of fillet welding costs based on a 40% duty cycle using 6 s.w.g. electrodes for single runs, with appropriate allowances for deslagging and changing electrodes, are listed on a relative basis in Table VI.

The contact types show a decided advantage for fillets up to $\frac{5}{16}$ in. leg length, the example in Table VI being for $\frac{1}{4}$ in. leg length. The reduction in costs for large multi-run fillets is much less, and may be of the order of 5–10% for the metal powder type. The convexity of fillets with non-contact types is wasteful in welding single-runs but is an operational advantage in depositing multi-run welds. The latest brands of metal powder electrodes are much improved over those originally available in their ability to produce large multi-run welds of equal leg length.

Butt welding

Estimates of butt welding costs on the same basis as for fillet welding are listed in Table VII.

Welding costs for butts show only a marginal difference between contact and non-contact types. When the surfaces of butt welds have to be finished, the saving in grinding costs may still justify the use of contact types. They may also be of value when their contribution to neater appearance, particularly after painting, is regarded as important.

6—12 ton mineral wagons

Application of Contact Electrodes

Types available

A number of brands for welding mild and high-tensile steels are available in each of the categories shown in Table VIII.

Table VIII

Available types of contact electrode

Category	*Type of Coating*	*Metal Powder, %*	*6 s.w.g. Coating Thickness, in.*
1	Rutile	—	0·05–0·06
2	Rutile	40–50	0·08–0·09
3	Low-hydrogen	20–30	0·07–0·08

Metal powder is incorporated in smaller amounts in some coatings, since it is a good thermionic emitter and confers improved arc stability. Such types may or may not be suitable for contact operation but are beyond the scope of this paper.

Non-metal powder types

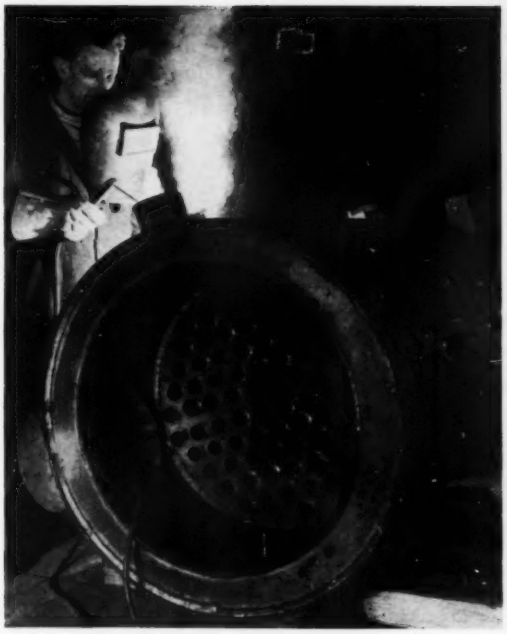
The non-metal powder type of electrode finds application mainly on relatively thin sections up to $\frac{1}{2}$ in. thickness, particularly where neatness and low cleaning costs are basic requirements and where fillets up to $\frac{1}{4}$ in. leg length are specified. Some brands give self-slagging welds which commend their use from the viewpoints of welder appeal and economy. A disadvantage is their higher cost for large multi-run fillets. Nevertheless their field of application is sufficiently large to make substantial savings possible. The welding technique required is close enough to that for non-contact types to bring their successful application within the ability of operators already skilled in the use of non-contact types.

Metal powder types

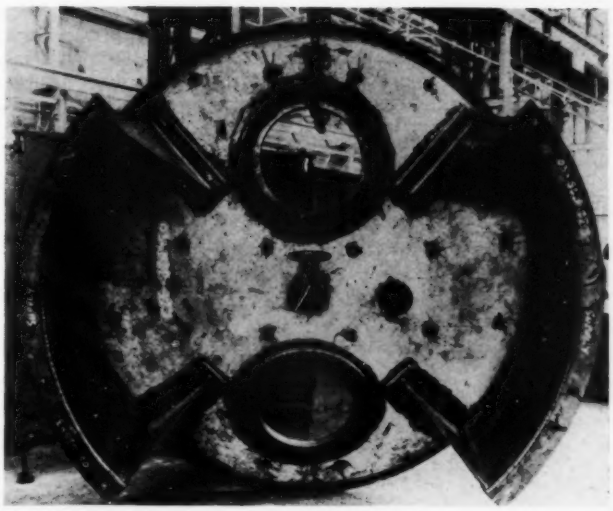
The range of application in fillet welding for metal powder electrodes is similar to that for non-metal powder types. The rate of deposition is, however, much higher and justifies the application of the metal powder type to prepared butt joints.

A major application is in repetition work on which the capital outlay for positioning equipment is justifiable. Figure 6 shows an example of successful application to 12 ton mineral wagons for which the bodies are fabricated in $\frac{1}{4}$ in. and $\frac{5}{16}$ in. mild steel plate. The size of electrodes used throughout was 6 s.w.g., and welding was carried out on a number of sub-assemblies positioned for welding in the flat and horizontal-vertical positions. A reduction in welding cost of 35% was achieved. In a further example, a 75% reduction in welding cost resulted from the use of metal powder electrodes with a simple manipulator for the hub-assembly of wagon wheels. Metal powder electrodes have also been successfully applied to 16 ton hopper wagon bodies fabricated in $\frac{3}{16}$ in. 'Corten' steel.

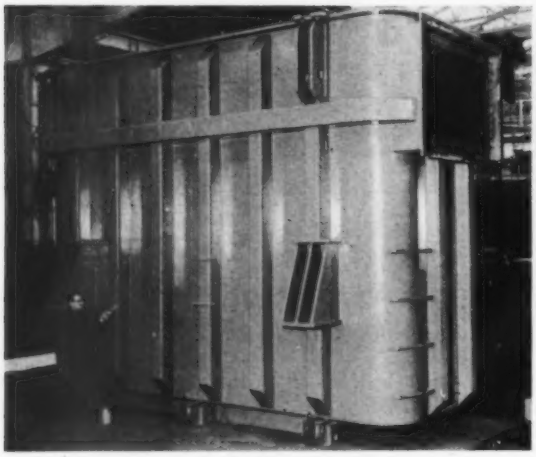
Figure 7 shows the use of this type of electrode for boilers produced in large numbers for heating greenhouses and for other purposes. Even without the use of positioning equipment a 10% reduction in cost was



7—Greenhouse boiler



8—Repairs to chemical plant



9—*Transformer tank*

10—*Switchgear controller tower*

obtained, and the number of leakage repairs found necessary was reduced from 10 to 2 leaks per 100 boilers.

Another useful application is for chemical plant repair work. For this, it is essential to return the plant to productive use in the shortest possible time. Figure 8 illustrates the type of work involved.

In a large engineering works producing fabrications of up to 50 tons, metal powder electrodes constitute 15% of the total amount used. It is planned to increase this figure eventually to 60%. A large transformer tank (Fig. 9) and a tower for switchgear liquid controller (Fig. 10) are examples of equipment welded with this type of electrode.

Experience shows that it is practicable to use the same core size or, in some cases, the next larger size of metal powder type as compared with conventional electrodes. Taking account of the metal powder content, this represents an equivalent size for the metal powder electrode of one or two sizes larger than the conventional type. This applies to the electrode sizes most commonly used—up to $\frac{1}{4}$ in. dia. The $\frac{5}{16}$ in. and $\frac{3}{8}$ in. sizes of the conventional type are of course used to a small extent, but their application is confined mainly to the flat position. A much larger proportion of work is welded in the horizontal-vertical position and it is for this work that the higher welding currents and higher deposition rates possible with metal powder electrodes have proved to be of such advantage.

Improved types are constantly becoming available and it is foreseen that metal powder electrodes will largely supplant their conventional counterparts as soon as they exhibit equal versatility in respect of suitability for multi-run fillets.

Acknowledgments

The author acknowledges helpful criticism during the preparation of this paper by his colleagues in the Heating and Welding Department of the A.E.I. Transformer Division.

BOOK REVIEW

A. VAZSONYI: "*Scientific Programming in Business and Industry*", London, 1960, Chapman & Hall Ltd. (John Wiley & Sons Inc.), 474 pp. (108*s*.)

Although management cannot be reduced to a series of equations, many of the problems of business and industry can be solved by a variety of new techniques based on mathematics.

These are now catalogued and described by A. Vazsonyi, in a way that the scientifically inclined manager or business man can understand.

Most of these methods have been appearing in the Industrial Engineering and Operations Research literature over the past 20 years but so far have not been used very much in industry.

This has partly been due to the lack of a book such as Mr. Vazsinyi now provides. Reading between the mathematics, it becomes clear that nearly every business has a choice of doing things in a number of different ways, and often only one of these ways will yield maximum profit. Management has first to discover where there are choices of action in the business. Next, adequate data about the factors affecting the choices must be made available. Correct application of the mathematical techniques then yields an answer.

To make sure that answers are obtained quickly enough to enable profitable decisions to be taken, the techniques must often be harnessed to efficient data collection and processing, including electronic computers.

The tools described by Mr. Vazsonyi include linear, convex and dynamic programming, the theory of games, statistical inventory control, machine shop and production scheduling. Few fabrication or engineering businesses could fail to find several applications that would be worth looking at. The book is well written and produced, deals adequately with the subject, and should be considered recommended, if not essential, reading for the scientific manager.

A. G. THOMPSON

SPRING MEETING 1961

Automatic Tungsten-Arc Welding of Heat Exchangers

(ESPECIALLY FEEDWATER HEATERS)

By N. T. Burgess, A.I.M., A.M.INST.W.

The development of satisfactory welding procedures for the welding of power-station feedwater heaters is described. Some early experiences with manual tungsten-arc welding are mentioned together with subsequent work on automatic welding guns. Some techniques devised in the U.S.A. have found use in the U.K. and note is made of American work in the welding of condensers. The processes described are well suited to the making of precision joints in tubular heat exchangers, and inspection methods are noted which should ensure reliability of plant in service.

THE conventional fixing of tubes into tube plates is by means of expansion, but with the availability of precision welding processes plant designers were able to consider this method to ensure a greater degree of reliability and leak tightness. For heat exchangers consisting of small-bore tube fixed into tube plate, of which the feedwater heater, condenser, and oil-cooler are typical, the argonarc welding process (hereinafter referred to as the tungsten-arc process) is particularly suitable, and this paper describes the development of satisfactory procedures for use in heat exchangers in the power generation industry. All the common engineering alloys can be welded in this manner but the choice of material is generally dictated by factors other than weldability.

Early Work

The inert-gas tungsten-arc welding process, using a non-consumable tungsten electrode in a shroud of argon, was first developed for the welding of magnesium and aluminium whose tenacious and protective oxide films prevented satisfactory welding by the conventional flux-covered processes. It was logical that this method of welding should be used quite early on for tubular aluminium alloy heat exchangers for the chemical industry. The process is equally suited for the welding of stainless steel, and again the construction of tubular heat exchangers lent itself to the process.

In power station feedwater heaters, boiler feedwater is passed into the tube nest through a water box and is heated by steam drawn from the turbine. Until recently, high-pressure feedheaters operated by the C.E.G.B. at about 1000 lb/sq.in. and at 400°F. on the water side have been built using tubes in various grades of cupro-nickel alloy, Monel, and mild steel, expanded into the tube plate. Modern power station practice calls for final feedwater temperatures up to about 500°F. and pressures up to about 3,000 lb/sq.in. for which mild steel tubes and headers are specified with welding as the preferred method of tube fixing (Fig. 1). As in the chemical or petroleum industries, expansion is adequate for normal pressures but these conditions require that there should be no risk of leakage leading to plant shutdown. At first the answer seemed to be to seal the edges of tube and plate by means of a circumferential weld round the top of the tube. This involves the use of the weld as a seal only, strength being obtained by normal expansion. In the first welded heaters provided for the C.E.G.B. at Littlebrook Power Station this construction gave trouble owing to leakage through the weld. After plant shutdown, inspection revealed the presence of porosity in the weld bead which probably provided a ready path of failure. The weld preparation included a machined groove $\frac{1}{16}$ in. deep round the hole to provide a spigot of similar thickness to the tube to which it was welded. Tube plate distortion was avoided by staggering the welding sequence, and a $\frac{1}{16}$ in. filler wire was used. At this time the hydraulic pressure test was the main means of testing the weld. Although only a light expansion is normally given to the tube, consideration was given to a full expansion before welding to provide extra strength. In general, expansion of tube into header was considered necessary to prevent vibration and possible failure of the weld by fatigue. In addition, the tube has to be securely positioned for manual welding. It was subsequently shown that this technique was responsible for the failures.

Manual welds, using a high Si–Mn filler wire, had

Manuscript received 14th February 1961.
Mr. Burgess is in the Research and Development Department of the Central Electricity Generating Board.

produced visually satisfactory welds with an average of 2% leakages on pressure testing. The failures were considered to be due to 'pin-hole' porosity and no cracking was encountered. During construction re-welding took place until a full pressure test of long duration could be sustained.

1—*Typical feedwater heater tube nest*

After the initial failures experimental work showed that sound welds could be produced by avoiding expansion before welding with tube positioning by tack welding. It was concluded that full expansion before welding probably trapped air or vaporized residual lubricant, or both, in or under the weld, and the expansion was then too tight to allow passage of air or vapours back down the tube as they expanded. It has therefore been necessary to recommend no expansion *before* welding but, if necessary to avoid vibration and possible corrosion fatigue, tubes may be given a *light* expansion *afterwards*. Care must be taken that, in doing this, no undue stress is placed on the weld itself.

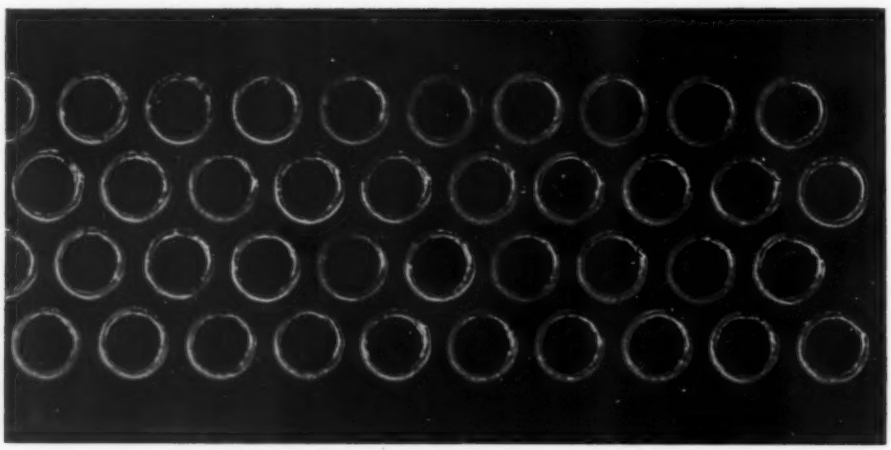
In other work in connection with heaters at Littlebrook Power Station no filler metal was added, and the tube was welded flush with the machined spigot in the tube plate. This was welded after a light expansion (20 lb torque compared with 80 lb for a full expansion). Again it was found that some porosity could occur, but this was generally associated with the crater, or with contamination by grease or moisture. Voltage step-down in conjunction with scrupulous cleanliness and steam jet cleaning etc. removed these causes and gave sound welds.

Fatigue

The removal of expansion lead to thoughts that fatigue of the weld might occur, and the C.E.G.B. undertook laboratory fatigue tests of some of the proposed joints (Table I). In other tests, carried out by the English Electric Co. Ltd., it was found that when the tube is free to vibrate failure can occur after some 10,000–20,000 reversals of load. When the welds are annealed or softened after welding the life is increased to 1½ million cycles.

Experimental heater

In conjunction with the English Electric Co. Ltd., the C.E.G.B. have installed a trial heater at Blackwall Point Power Station fabricated by manual tungsten arc welding. To support this a laboratory programme was carried out on test plates made by various techniques; the plates were then reduced in thickness to



2—*Test plate of edge welds for radiographic examination*

Table I

Fatigue properties of some internal bore welds compared with ordinary expanded joints

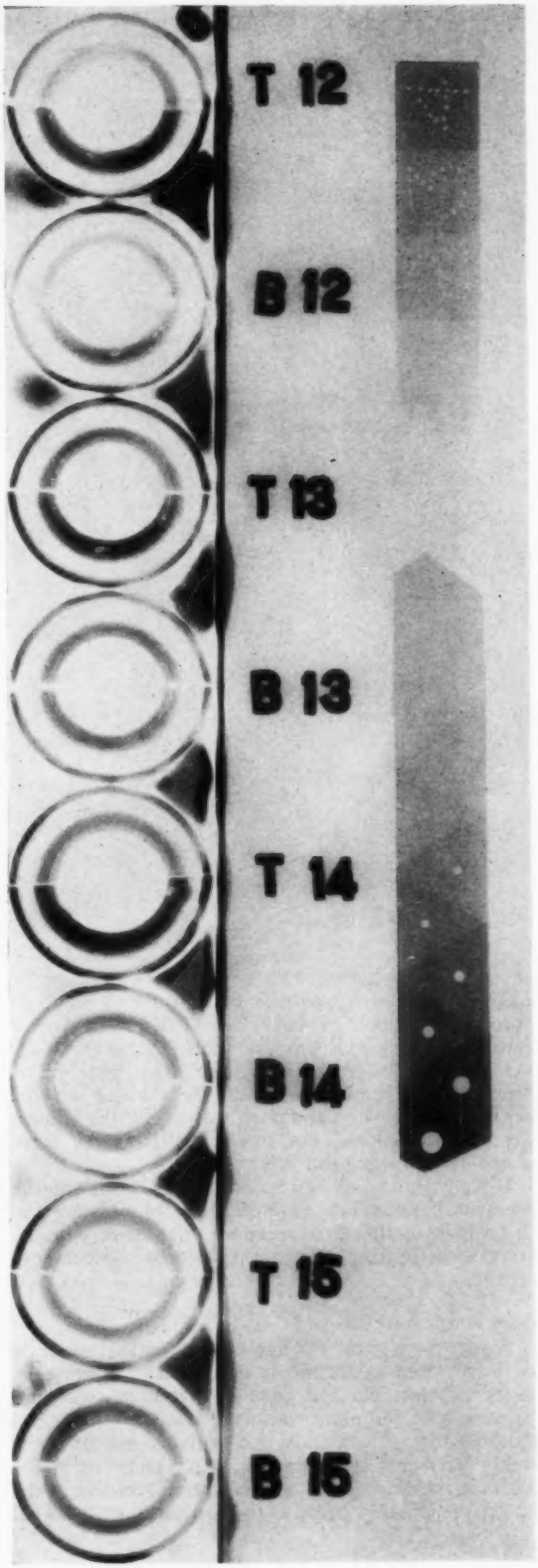
Joint	*Maximum Fibre Stress, tons/sq.in.*	*Number of Cycles* $\times 10^6$	*Remarks*
1E	7·33	18·99	Unbroken
,,	9·11	48·44	,,
,,	11·65	0·98	—
2E	9·82	9·99	—
3E	8·19	22·49	Unbroken
,,	9·58	18·71	,,
,,	11·55	2·26	—
4E	10·59	2·26	—
5E	10·18	49·20	Unbroken
,,	10·96	2·27	—
6E	10·60	4·32	—
1W1	10·60	20·80	Unbroken
,,	12·34	50·80	,,
,,	14·15	35·56	,,
,,	15·16	5·36	,,
,,	18·04	0·41	—
2W1	16·90	1·67	—
3W1	17·84	2·03	—
4W1	17·08	2·35	—
5W1	16·67	3·16	—
6W1	16·91	2·68	—

make them amenable to radiography (Fig. 2). At the outset it was found that simple macro-sections of welds were not a satisfactory guide to weld quality. After radiography the welds were ground down progressively to remove 0·010 in. of metal at each cut so as to reveal any defects through the depth of the weld. Welds were made on semi-killed steel plate, and pull-out strengths varied between 6,000 and 8,000 lb.

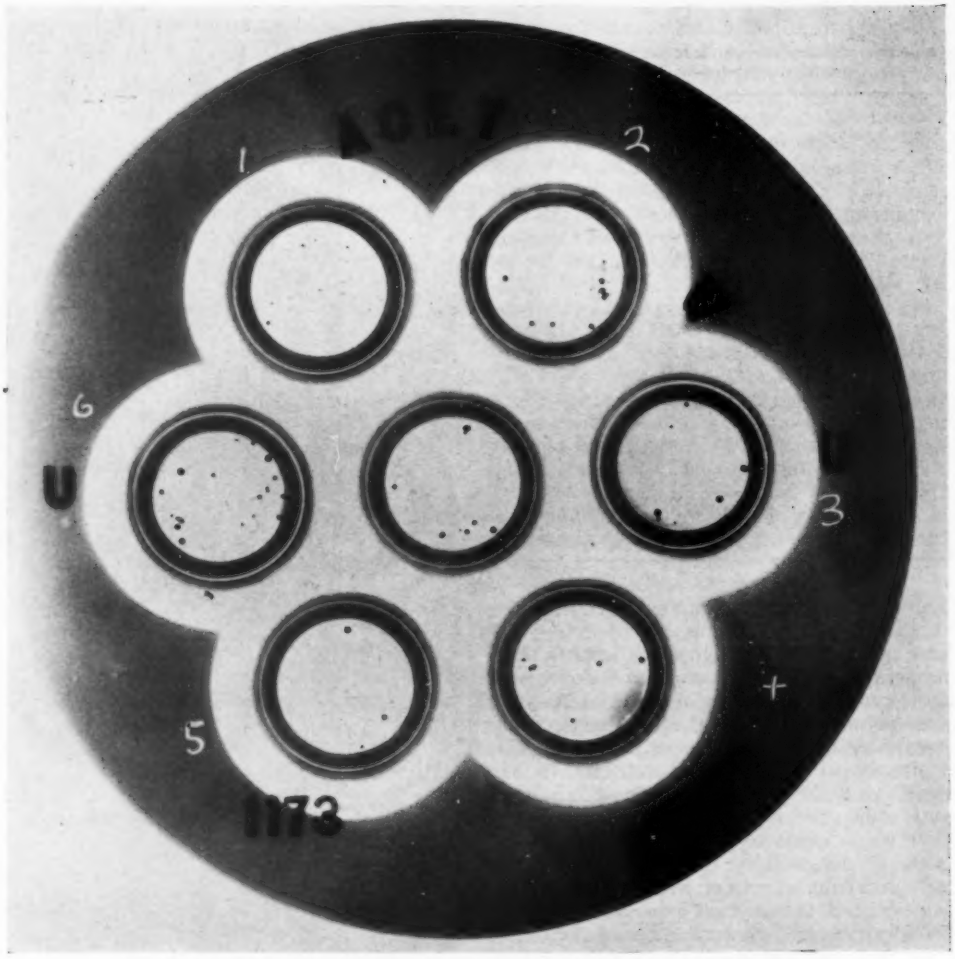
The experiments showed that considerable amounts of porosity could arise if cleaning was not adequate, and repeat welds made under clean conditions removed most of the porosity. (Fig. 3 shows the type of porosity occurring in similar work on this topic.) But it was difficult to avoid all porosity unless the correct welding conditions were automatically controlled. Any porosity present was probably a result of the CO/CO_2 reaction and accordingly experimental welds were made with the addition of deoxidants. A single coating of aluminium paint improved the quality but the technique is not reproducible and is not consistent in its results. A preplaced ring of filler metal containing deoxidizing elements was successful in removing all traces of porosity.

To assist positioning of the tube in the tube plate for welding, the heater was arranged horizontally, welding being carried out in the vertical position using a pencil torch at about 90 amp. To assess the benefits of expansion, only one half of the heater tubes were expanded after welding. The heater was further divided into quadrants, half of the welds being post-heated after welding in an attempt to reduce the likelihood of hard spots. Inspection was by dye penetrants followed by complete hydraulic testing of the finished heater.

After 220 hr service some leakage occurred at three out of 600 welds. In two instances this was due to a fault in machining which gave a too thin lip of metal,



3—*Radiograph of 16 half welds, showing porosity at joint line*



4—*Radiograph of oxy-acetylene welds. (The spurious black spots are lead fragments)*

and in the third it was due to an isolated patch of porosity that would probably be avoided by the use of automatic welding. Repairs were effected by metal-arc welding and, after further work, leak tight welds resulted. No conclusion could be reached on the benefits of expansion and post-heating, for the failures were not indicative, but the heater has now completed several thousand hours service.

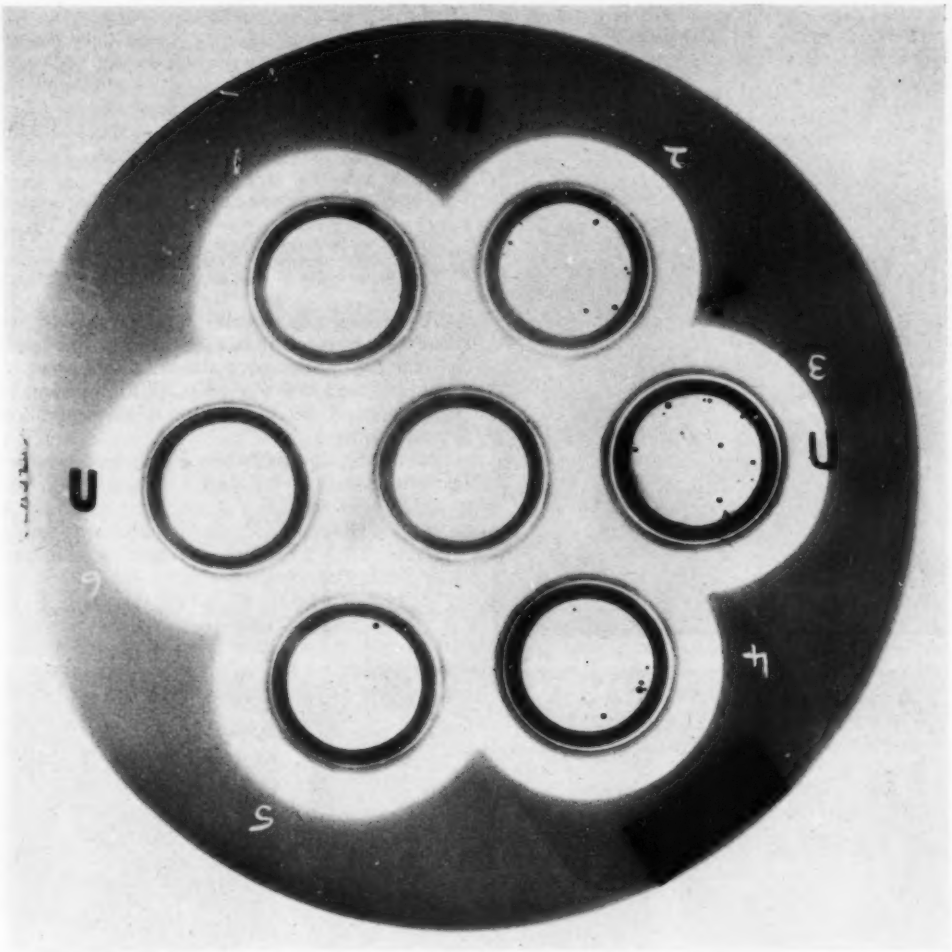
Difficulty in repair can be experienced owing to the presence, between tube and tube plate, of moisture and rust which is difficult to remove prior to re-welding. Some local heating is therefore recommended before repair.

Other experimental work

Work in Germany[2,3] has confirmed that there is porosity when expansion is done before welding. A series of tests showed that any residual moisture between tube and plate evaporates during welding and that residual air expands and remains sealed in the weld. Further tests, comparing oxy-acetylene welds with tungsten-arc welds, show greater porosity in the latter, presumably because the top crust of the weld freezes more quickly than with oxy-acetylene, so entrapping any gas. In Germany, therefore, gas welding of tubes to the tube plate is recommended.

Several individual studies have been made of the welding of mild steel heaters, and before tungsten-arc welding was agreed on as the best method, metal-arc, oxy-acetylene, and atomic hydrogen welding were all proposed as a solution to the problems. Metal-arc welding, using a bulky electrode, is not applicable to small peripheral welds of this type and cannot be suitably mechanized. Such test welds as were made indicate satisfactory penetration and fusion but also a rough exterior finish which might impede fluid flow.

As mentioned previously, oxy-acetylene welding has been shown to produce good welds,[2] although this process also is not really adaptable to mechanization. The greater heat input involved in obtaining fusion provides a longer solidification period during which the weld can release gas or other impurities that may be otherwise trapped by a fast-freezing weld. The hardness of such welds is also reduced. The atomic hydrogen process has been used in making experimental welds but results are not as good as with other



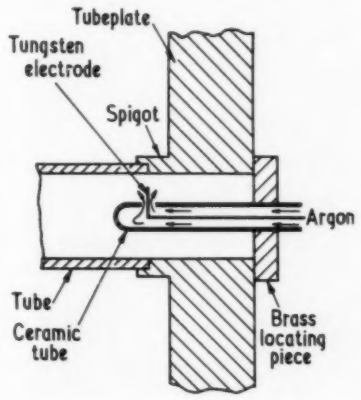
4—*Radiograph of atomic hydrogen welds showing dispersed porosity. (The spurious black spots are lead fragments)*

methods, although the process lends itself to small detail welds of this type. Figure 4 is a radiograph of welds made by oxy-acetylene and atomic hydrogen welding.

Internal Bore Welding

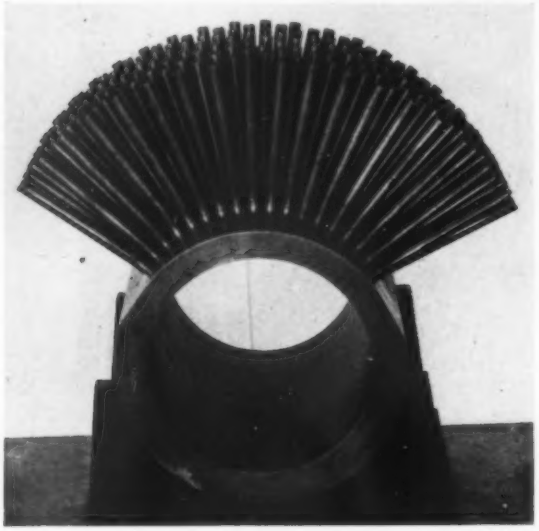
Following the experiences mentioned, the manufacturers of feed-heating plant have given consideration to producing welds automatically. With up to 1,000 precision welds per heat exchanger, welder fatigue using a manual process is a likely source of defective welds. In addition, consistency of weld quality and speed of welding are significant factors in choosing an automatic process. The C.E.G.B. were approached by Foster Wheeler Ltd. to decide whether an internal bore automatic tungsten-arc process they had developed for heat exchangers for nuclear purposes would be suitable.

This process relies on the butt welding of small bore tubes from the inside of the tube (Fig. 5). The torch assembly consists of a tungsten electrode arranged to project at right angles through an opening in the wall of a tubular housing, which is located co-axially in the tube. The assembly incorporates the supply of electric current, argon gas, and cooling water. Control is automatic and, once the conditions are established, a



5—*Principles o internal bore welding.*

series of welds can be completed by pressing a starter button at the commencement of the welding sequence. Satisfactory welds have been made in a range of materials, but for current feedheaters the tubes and plate would invariably be of mild steel. An internally welded tube bundle is shown in Fig. 6.



6—*Internally welded tube bundle exhibited at "Atoms for Peace" Exhibition, Geneva, 1958*

Examination of early samples indicated that hard zones could occur in the weld and in the H.A.Z. owing to the excessive chilling of the small weld zone by the solid metal of the header plate. Typical microsections are given in Fig. 7.

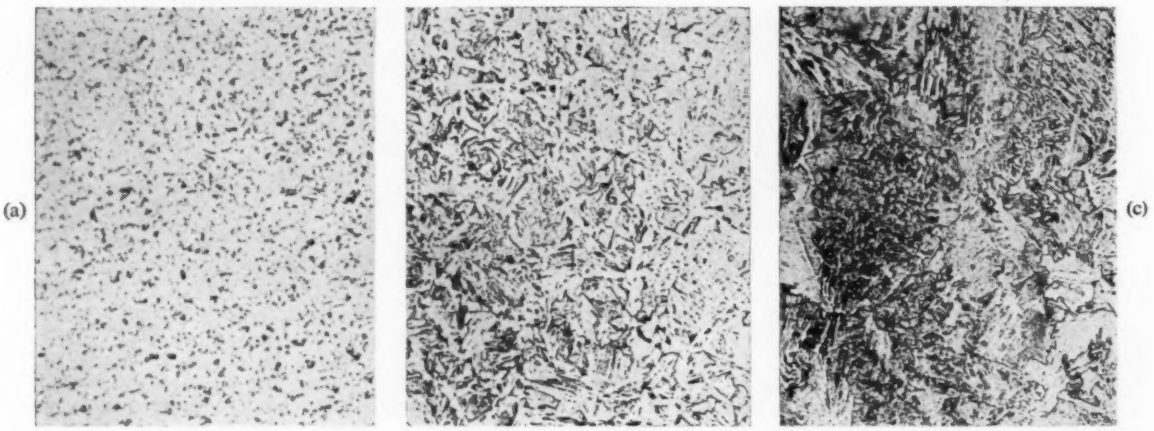
Three methods exist for reducing hardness:

(i) Limitation of the carbon content
(ii) Preheat-treatment of the joint to avoid excessive chilling
(iii) Use of a higher stub so that chilling will be less.

A series of experiments were carried out using preheat temperatures of 200° and 400°F. in an attempt to reduce the hardness of the zones. However, in this instance a reduction of only 20–30 points in hardness resulted, and an increase in stub height offered a better solution.

A suitable composition of plate and tube would be as follows:

	C, %	*Si*, %	*S*, %	*P*, %	*Mn*, %
Tube	0·14	0·13	0·018	0·023	0·61
Plate	0·18	0·10	0·029	0·016	0·63



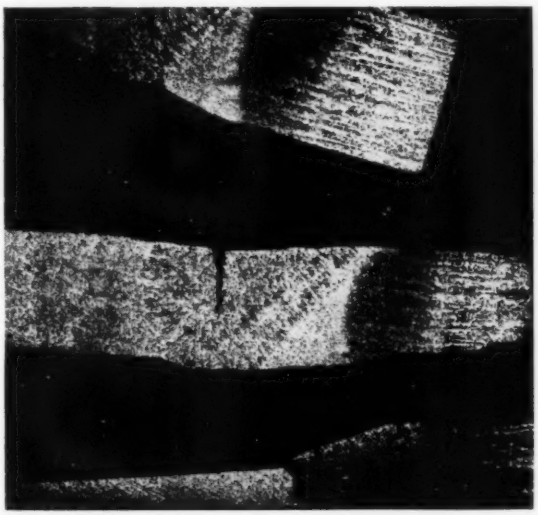
7—*Microsections across weld area of internal bore weld in mild steel;* (a) *Tube material;* (b) *tube H.A.Z.;* (c) *weld metal;* (d) *bar H.A.Z.;* (e) *bar material* ×150

It is not, however, always practical to restrict the carbon too far and preheating can introduce extra cost and delay. Hot cracks (Fig. 8) can occur if the chemical composition of the plate is not controlled or if the parent metal hardness is excessive, so that plate should be in the normalized rather than the 'as rolled' condition. Careful attention to welding variables and cleanliness can usually overcome many difficulties. Porosity has not so far been a problem with internally made welds. Sound welds have been produced in tubes up to $1\frac{1}{4}$ in. o.d., and an advantage of this process is that the proximity of other tubes does not restrict welding.

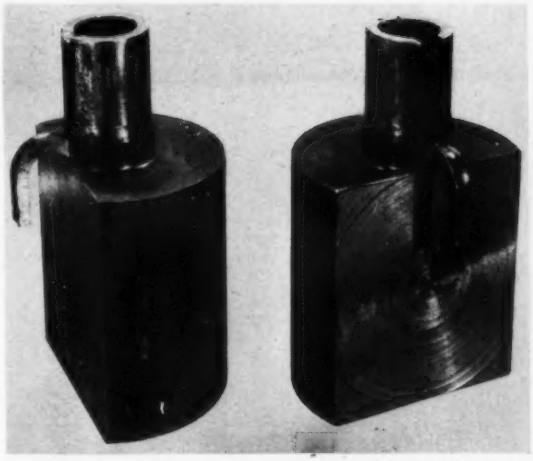
The process is attractive because it offers a method of *butt* welding tubes to headers and, on past experience, less trouble has been experienced with this type of weld than with fillet or edge welds. Each weld is a full strength weld with no notches which might initiate a crack, and the design is such that no crevice exists between tube and plate. Also the holes in the tube plate are reduced in diameter. Ligament strength is thus improved resulting in a thinner tube plate, or alternatively a smaller diameter tube plate because of the closer tube pitch.

The C.E.G.B. undertook fatigue tests on a small number of tubes and it soon became apparent that the radius at the root of the preparation must be a minimum of $\frac{1}{8}$ in. or fracture would occur at this point. With properly machined test pieces fracture normally occurs above the weld in the tube but on some specimens failure started at the toe of the weld. Typical fatigue data for such welds, compared with conventional expanded joints, are given in Table I.

It is suggested that tube bundles should be welded in the vertical position to provide easier fit-up and to enable flux to be placed round the welds. It is of prime importance that the exact location of the tungsten arc relative to the abutting faces should be determined accurately to enable full penetration to be achieved, and distance pieces are used for accurate positioning.

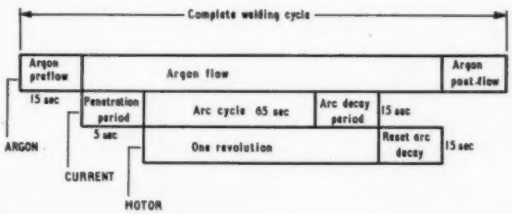


8—*Hot cracking in high carbon plate*



9—*Bend tests on 1% Cr-$\frac{1}{2}$% Mo tubes ($1\frac{1}{4}$ in.o.d. 8 s.w.g.) to mild steel base*

Absolute cleanliness is also essential, for dirt and grease cause defects in the weld that are not tolerable. Tubes should be degreased with acetone or carbon tetrachloride after they are threaded through the baffle plates and immediately before welding. A flux surrounds a number of the welds in position, the gun is inserted into the first tube and the welding sequence is set in motion. For example the current for welding a 12 gauge tube to a plate with a $\frac{1}{4}$ in. stub is likely to be 70–90 amp. The cycle is carefully timed, a typical sequence being:

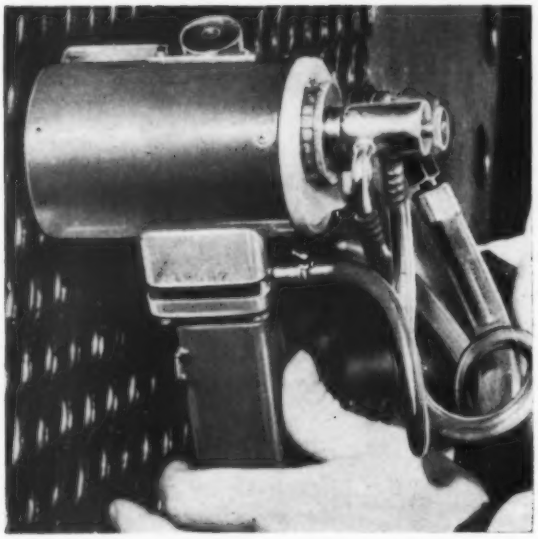


The de-superheating section of a high-pressure heater at Northfleet power station and a h.p. feedheater at Aberthaw power station will shortly be in service with tube joints welded by the internal bore method.

Experience with this technique has also been gained during the welding of marine steam generators. In this case the components were in a 1% Cr–$\frac{1}{2}$% Mo alloy steel, and no significant troubles have been reported (Fig. 9 indicates the ductility of the weld). Owing to the severe risks involved if leakage through the joints occurred, strict quality control methods were exercised throughout production in respect of clean working conditions and materials. In addition, all joints were tested by halogen leak testing methods mentioned later.

Revere Process

In America, most developments in this field have been centred round the welding of copper alloys,

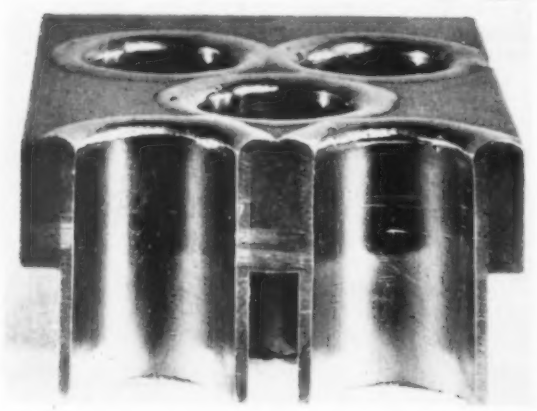


10—*Revere welding gun*

which are widely used for feedheating and condensing plant. The copper and brass companies have therefore developed welding procedures and will undertake construction and maintenance of copper alloy plant as a service to the user.

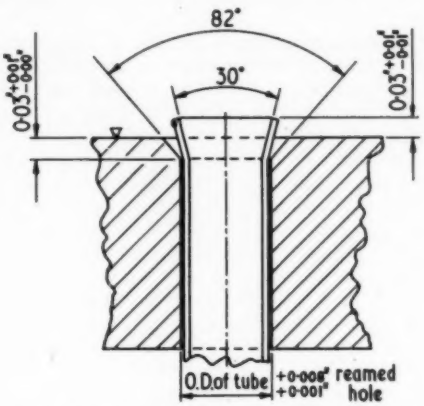
Revere Copper and Brass Incorporated have directed much attention to this activity and full reports of their work are available[4, 5]. Their process is licensed in the U.K. by Heat Exchangers Ltd. (a subsidiary of the Superheater Company) who, whilst they have experience of the technique on several different materials, also draw on Revere for full technical information (Fig. 10).

The first British use of the process was for three large heat exchangers (involving 24,000 welds) which were constructed here during 1960. These were in 18/8 stainless steel and involved tubes 1 in. o.d. × 16 s.w.g., the construction being to insurance company approval.



11—*Welds between cupro-nickel tubes and mild steel plate*

Monel and Inconel heat exchangers have also been welded by this process using a filler ring. Other relatively 'clean' materials are readily welded by the process, which does not normally need a filler (Fig. 11). Much development work has been directed towards obtaining efficient welds by experimenting with different weld preparations. The preparation of tube and plate that has been found to give reliable welds with minimum machining costs is illustrated in Fig. 12. The cutting angle of a Standard American drill is 82° and any defective welds can therefore be removed



12—*Plate and tube preparation specified for use with Revere process*

rapidly and cleanly. In the U.S.A., a test weld was drilled and rewelded 21 times to establish the suitability of this procedure for repair purposes. The absence of a machined spigot or stub would seem to avoid the risk of dirt entrapment before welding.

Some manufacturers of feedheating plant have shown interest in this process for the welding of high-pressure, mild steel tubed feedheaters and they, together with the C.E.G.B. have examined a large number of welds. Experience with the use of this process on mild steel is, however, limited to the U.K. and more work is required before it becomes as widely used with steel as it is with the non-ferrous metals.

In connection with development work for the h.p. feedheaters for Richborough Power Station, a test plate comprising 33 welds has been made. The tube plate was $3\frac{5}{8}$ in. thick by 10 in. dia. in a steel of the following composition:

C, %	*Si*, %	*Mn*, %	*S*, %	*P*, %
0·17	0·24	0·091	0·031	0·046

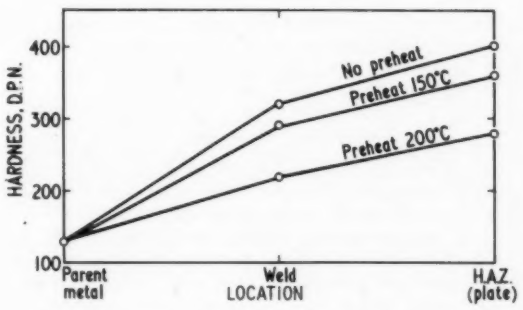
A small V was machined round the lip of the tube hole, $\frac{1}{16}$ in. deep and 45° round the periphery. This was the only preparation, and the tubes were then located by means of a light swageing with a hammer and a tapered plug and welded at about 115 amp d.c.

This sample plate was hydraulically tested at 1,500 lb/sq.in. for 24 hr with no sign of leakage. For a brief period during this test the pressure was raised to 2,000 lb/sq.in. A sensitive leak test was carried out in which a gas comprising 90% nitrogen and 10% N_2O was passed into the test unit at 1,000 lb/sq.in. Using a

Speedivac gas detector no leaks could be detected over the test period. Pressure was applied to the outside of the tubes and the probe was applied to the surface of the weld. This test was repeated after the tubes had been expanded into the header, again with no evidence of leakage.

Push-out tests (under loads of 3–4 tons) were carried out on a selection of welds, and in each case failure occurred in the tube rather than at the weld. Radiography of the welds, carried out by thinning the tube plate to $\frac{1}{2}$ in., indicated slight porosity in two of the welds, but in each case this was associated with the current decay point, occurring after a full circle had been welded. This should be overcome by suitable adjustment of mechanical and electrical controls.

In the initial trials a hardness exploration indicated that the weld metal can in some circumstances have a hardness of up to 350 D.P.N. These levels are unacceptable for service conditions where fatigue or thermal shock could initiate a failure in a brittle type material. Further tube plates have now been welded using various degrees of preheat in an attempt to reduce the hardness peaks in the heat affected zone. Figure 13 indicates very roughly the pattern of hardness values and confirms that a preheat of 200°C. is required to obtain acceptable levels of hardness where control of composition does not achieve this effect.



13—*Effect of preheat on hardness in weld and H.A.Z.*

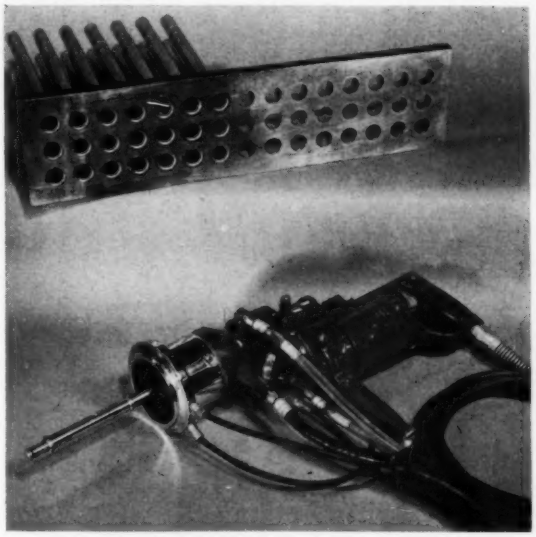
Other British Developments in Automatic Welding

A.E.I. Ltd. have developed an automatic welding gun and a procedure based on their considerable experience with manual welding. This uses d.c., with the electrode negative, together with a thoriated tungsten electrode. No preheating is required, the sequence of welding being carefully controlled to keep distortion to a minimum and to avoid defects.

The English Electric Co. Ltd., following on work mentioned earlier, have also developed an automatic gun that is used with a filler ring to achieve optimum soundness.

American Developments

At the Knolls Atomic Power Laboratory in America techniques developed originally by Griscom-Russel Co. have been tried for tube to tube sheet joints for nuclear plant heat exchangers.[7] Type 347 stainless steel tubes and sheet have been internally welded in this manner in sizes down to $\frac{1}{4}$ in. i.d. All welds passed the crack detection and leak tests but X-ray techniques were not considered to be reliable. In tensile tests, strengths up to 40 tons/sq.in. (equal to that of annealed parent metal) were realized with fracture in the softer weld metal. Typical conditions for stainless steel in these dimensions are:



14—*Automatic gun produced by A.M.E. Co. in America*

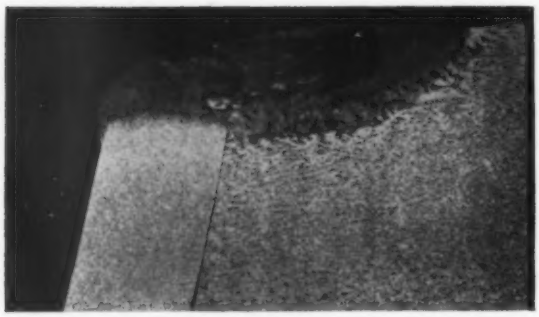
Argon flow	*Current* (d.c. elec.-ve)	*Arc length*	*Rotation*	*Weld Speed*
6 cu.ft/min	29–31 amp	0·020 in.	10 sec	7·5 in./min

Welding condensers

The design and operation of modern power plant requires that tubes in condensers should be installed permanently tight to prevent contamination of the boiler feed water. Welding ensures this and a mechanized process must be employed to produce consistently high quality joints.

The availability of automatic welding guns in the U.S.A. has already been mentioned. Figure 14 shows one such gun provided by Automation Machines and Equipment Co. Wisconsin, U.S.A. Good results are claimed for the welding of cupro-nickel to cupro-nickel and cupro-nickel to steel. With the gun illustrated the electrode is mounted perpendicular to the plate surface. Welds are relatively shallow especially if heat input and arc path are adjusted to avoid weld overhang that would obstruct the bore. Absence of filler metal that would help bridge the joints requires that tubes should be tight against the hole walls, otherwise tubes and plate melt separately and will not fuse together. Welding is by electrode negative d.c., which gives maximum life to the tungsten electrode, resulting in more reliable welds over the production period.

Most condensers are Admiralty Brass or aluminium brass tubes in plates of similar material. Admiralty Brass tubes have been welded to Naval Brass plates in many instances (Fig. 15). Other copper alloy combinations can be successfully welded but arc length must be controlled more closely and there may be difficulty in



15—*Weld between arsenical Admiralty Brass tubes and Naval Brass tube sheets*

making repair welds. Zinc-bearing alloys are difficult to weld with direct current, but a.c. can be used successfully especially if the gas shield is argon plus helium, although the method is not feasible for site welding. A readily welded tube plate material is silicon bronze, but British condenser plate manufacturers are unable to supply this material in the required sizes at present. Weldability is improved by the lower conductivity and absence of zinc in the silicon bronze, and penetration is reported to be greater with higher strength and smooth contours, even when the material is welded in the vertical position normally required for site welding of condensers. In American practice for copper alloy tubes to steel headers a barrier layer of metal (generally nickel) is used and is first deposited on to the steel header plate. Monel is also used for this purpose. Overlaying is local to tube holes or is general, using automatic inert-gas consumable-electrode or metal-arc processes.

Inspection of Welds

Although welds can be visually examined and the extent of penetration confirmed it should be possible to inspect the weld by a non-destructive method, and the C.E.G.B. Research Laboratories are currently looking into this.

A small dental X-ray or gamma-ray probe placed inside the tube might be applicable to the inspection of internal bore welds. Alternatively a representative number of welds could be radiographed by placing a film behind, say, twelve tubes and introducing the X-rays at an angle. If this were done only for the initial production runs, careful control subsequently should ensure that all the welds are of similar quality. At present, however, inspection is mainly visual, using an 'Introscope' tube viewer coupled with leak testing devices that are extremely sensitive. The halogen 'sniffer' technique uses a sensitized cell to record the presence of halogen leaking through the weld under pressure and this can be measured audibly or visually. Nitrous oxide gas is used in a similar way. With edge welds similar techniques are being used.

An ultrasonic method has also been developed by Sproule[8] involving an immersion technique in which longitudinal waves are reflected from an aluminium block in the bore of the tube into the centre of the small weld bead. By rotating the probe, which is placed centrally above the weld, the beam scans the whole circumference of the weld and defects can be recorded on an oscilloscope. At the present time the results from the use of the technique have not been conclusive however and work is still continuing. The instrument is very sensitive and the internal bore of the tube has to be very clean to obtain satisfactory results. Final testing of welded feedheaters is by conventional methods for a pressure component of this type and a hydraulic test is a final check that welded joints made by any of the recently developed methods are sound and capable of giving reliable service.

Conclusions

This paper has summarized developments in the automatic welding of certain types of heat exchanger. Experience to the present time has shown that welding is an acceptable method of fixing tubes into tube plate but that close attention to welding procedures is essential. Automatic control of the tungsten-arc welding process enables high quality welds to be made which are substantially free from porosity and entirely free from cracks.

Although manually welded heat exchangers have been in use for many years in the U.K. the first automatically welded feedwater heaters will only come into use during 1961. The experience gained in their construction and successful operation will be of value in other high-pressure components and in the use of these automatic welding methods in other fields. Meanwhile experimental work to improve still further the reliability of welds is continuing in the laboratories of the manufacturers and the Central Electricity Generating Board.

Acknowledgments

The author acknowledges with thanks the helpful assistance of Foster Wheeler Ltd., Heat Exchangers Ltd., G. and J. Weir & Co. Ltd., English Electric Co. Ltd., Anaconda Copper and Brass Inc., and his colleagues at the C.E.G.B., especially Mr. L. H. Levene of the Power Plant Design Branch. He also wishes to thank the Central Electricity Generating Board for permission to publish this paper.

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SPRING MEETING 1961

By B. H. Baker, N. Crevis, J. A. Lucey and F. W. Lunau

Mild Steel Welding with Argon/CO_2 Mixtures

Investigations into the performance of mixtures of argon and CO_2 for the bare wire gas-shielded welding of mild steel show that these mixtures, in the range containing 20–25% CO_2, have features not possessed effectively by either argon/O_2 or CO_2.

Weld bead shape is better than with either of the constituent gases. For welding with the metal being transferred under free flight conditions, a spray type of transfer can be obtained, and in dip transfer welding stable conditions can be obtained at voltages 2–3 V lower than with CO_2.

These features lead to economic advantages over the use of CO_2 for welding sheet metal and to operational advantages for welding plate $\frac{1}{4}$ in. thick and over.

THE successful use of metal-arc welding with a bare electrode wire and protective gas shield stems from the discovery that in an inert gas the mode of metal transfer from the electrode is greatly affected by both the electrode polarity and the current density in the electrode. With the electrode connected to the positive pole of a d.c. power source and a current density of the order of 50,000 amp/sq.in. or more it was found that aluminium could be deposited in a fine spray of droplets producing sound, good looking welds.

Before this new process could be applied successfully to mild steel fabrication two problems had to be solved—how to cope with the oxygen present in rimming quality and semi-killed steels, and how to improve the wetting action to prevent a tendency towards undercutting. These difficulties were overcome by using highly deoxidised filler wires and a mixture of a small percentage of oxygen in the argon, whereby the process was capable of producing high-quality welds in commercial qualities of steel.

The principal limitation then became an economic one since, although the bare-wire process offered higher deposition speeds, the saving in labour and overheads was offset by the higher combined cost of consumables, and the resultant economy compared with manual electrodes tended to be marginal. This led to the use of CO_2 as a shielding gas in place of argon/O_2, and some applications were established which were economical as well as technically satisfactory. Widespread use of the process has however been restricted, principally owing to the limited range of welding conditions over which spatter can be kept to a minimum, and acceptable weld shape and quality maintained.

Investigations into the effects of mixing argon and CO_2 were reported as early as 1956.[1] In Britain more thorough investigations into the potential advantages of using argon/CO_2 mixtures were given considerable impetus by the development of new equipment for feeding fine wires, and new types of power sources.[2] In recent months their use has grown intensively in the U.S.A. particularly for welding mild steel sheet, while some use has been made in Germany[3] of a gas mixture containing oxygen in addition to argon and CO_2.

These mixtures have been found to have many of the best characteristics of their constituent gases, and this paper describes work done to examine the technical features of these mixtures more closely, to find an optimum composition, and to compare its merits with those of argon/O_2 and CO_2 shielding gases.

General Procedure, Materials and Equipment Used

Preliminary work indicated that the gas mixtures that gave the best overall welding performance contained from 12 to 25% CO_2, and the present investigation covers a closer examination of the performance of a number of gas mixtures in this range. The gas mixture that gave the best results was then compared with CO_2 and standard argon/O_2 mixtures (Table I).

Tests were carried out with a variety of welding equipment. For semi-automatic welding portable push-type wire feed units were extensively employed with both lightweight and heavy-duty torches, and also self-contained lightweight guns. For fully automatic welding a standard welding head, a specially designed and fully instrumented automatic head, and a tractor-mounted self-contained gun were used.

The principal power sources used were constant potential and shallow drooping transformer rectifiers

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Table I

Gas mixtures used

No.	Nominal Percentage Argon	Carbon Dioxide	Oxygen
1	98	—	2
2	95	—	5
3	85	15	—
4	85	13	2
5	80	20	—
6	80	18	2
7	80	15	5
8	75	25	—
9	75	23	2
10	—	100	—

Table II

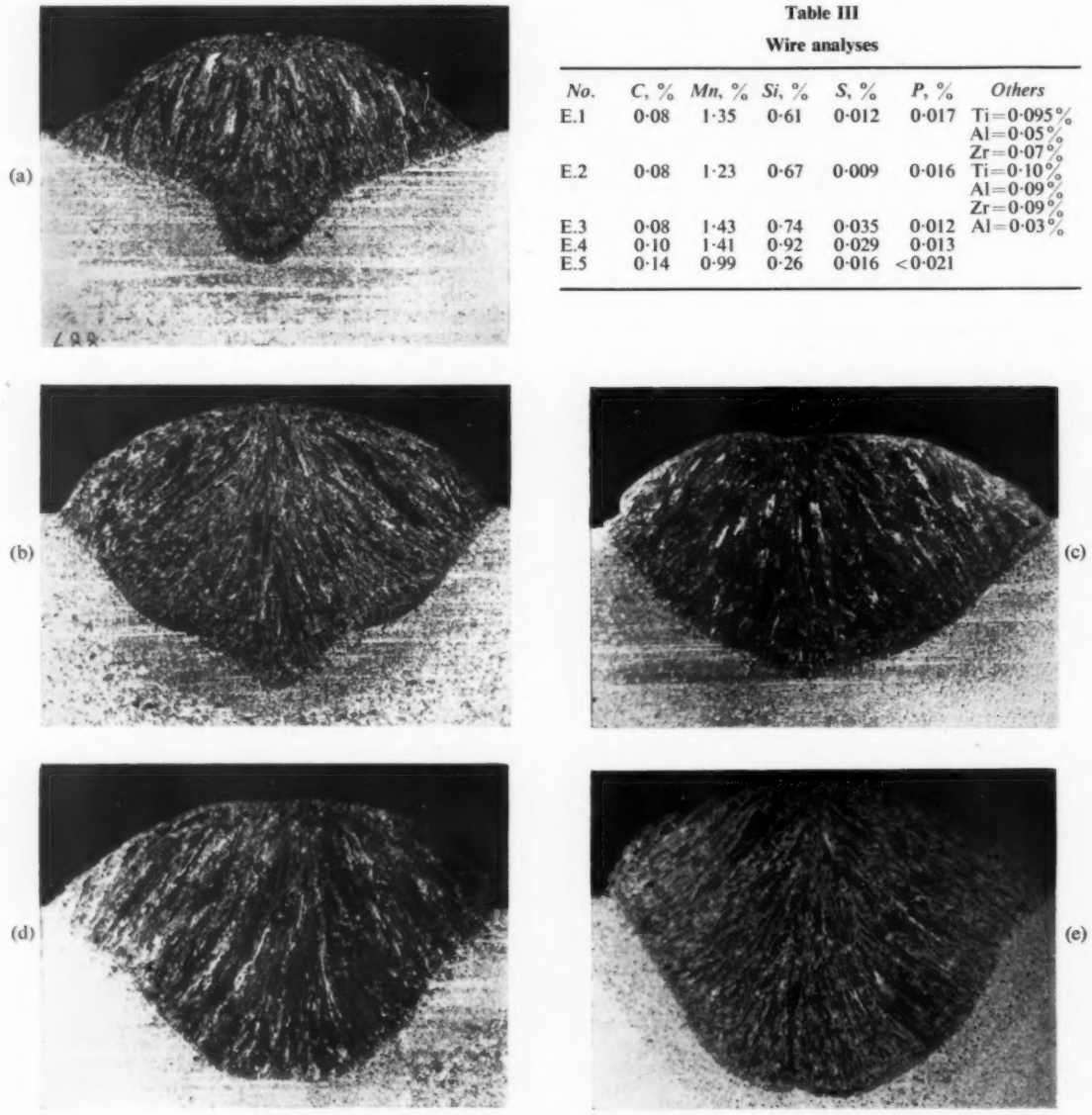
Typical plate analyses

No.	C, %	Mn, %	Si, %	S, %	P, %	Classification
P.1	0·19	0·40	0·054	0·024	0·028	Balanced
P.2	0·12	0·44	0·02	0·054	0·057	Balanced
P.3	0·10	0·65	0·05	0·027	0·02	Balanced
P.4	0·10	0·36	0·01	0·041	0·01	Rimming
P.5	0·15	0·83	0·10	0·029	0·025	Fully killed
P.6	0·047	0·36	0·002	0·028	0·011	Rimming
P.7	0·106	0·78	0·03	0·023	0·033	Balanced
P.8	0·19	0·59	0·025	0·031	0·025	Balanced
P.9	0·17	0·63	0·22	0·031	0·019	Fully killed
P.10	0·24	1·68	0·21	0·039	0·035	Fully killed
P.11	0·51	0·95	0·25	0·029	0·026	Fully killed

Table III

Wire analyses

No.	C, %	Mn, %	Si, %	S, %	P, %	Others
E.1	0·08	1·35	0·61	0·012	0·017	Ti=0·095% Al=0·05% Zr=0·07%
E.2	0·08	1·23	0·67	0·009	0·016	Ti=0·10% Al=0·09% Zr=0·09%
E.3	0·08	1·43	0·74	0·035	0·012	Al=0·03%
E.4	0·10	1·41	0·92	0·029	0·013	
E.5	0·14	0·99	0·26	0·016	<0·021	



1—*Weld bead profiles:* (a) *98% A, 2% O_2;* (b) *85% A, 13% CO_2, 2% O_2;* (c) *80% A, 20% CO_2;* (d) *75% A, 25% CO_2;* (e) *100% CO_2*

for the higher currents, and slope-controlled transformer rectifiers for dip transfer welding.

For measurement of current and voltage both direct reading and recording instruments were used, calibrated against precision grade instruments. Where particularly accurate measurements of wire and traverse speeds were necessary they were made by means of stroboscopic discs on the driving motors.

Metal transfer was studied both by means of an oscilloscope and by high-speed photography, using a high-speed camera capable of framing rates of up to 4000 per second.

The compositions of the plate materials and wires used are given in Tables II and III.

Comparative Tests with Argon/CO_2 and Argon/CO_2/O_2 Mixtures

The tests to determine the best gas mixture were carried out using dip globular and spray modes of metal transfer.

Bead shape

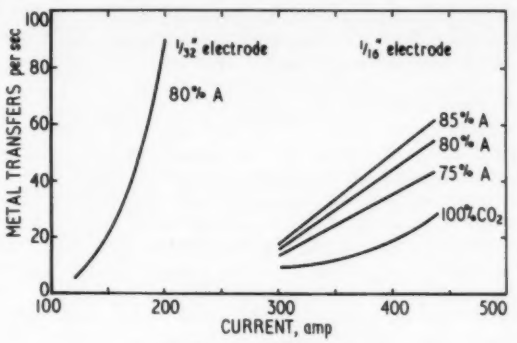
Bead-on-plate runs were made at a current of 370 amp using $\frac{1}{16}$ in. electrode E1 (Table III), the traverse speed being adjusted to give a constant reinforcement. Semi-killed plate P1 (Table II) $\frac{3}{4}$ in. thick was used as the workpiece, since it was thick enough to avoid any interference with weld bead shape by change of heat transfer characteristics with change in penetration.

Bead widths were not significantly different for the seven gas mixtures at the same voltage, but with a given gas bead width increased with voltage. Penetration decreased with increase of voltage, and for a given voltage was not markedly different for any of the seven gas mixtures. There was also little difference in the ratio of bead width to penetration, it being between 3·0 and 3·5 over the useful range of welding conditions. The ratio of reinforcement area to penetration area was about 0·6 for all mixtures.

In general these results showed that the effect of argon/CO_2 mixtures, with or without oxygen, is much as would be expected from the arc characteristics of the component gases. The pronounced finger-type penetration obtained with argon, which, it has been suggested, is due to the plasma jets associated with the sharply defined ionization core characteristic of a monatomic gas,[4] is modified as the amount of polyatomic CO_2 is increased. When there is 100% CO_2 present a deep general penetration is produced. This is shown in Fig. 1 where finger penetration is present with argon/O_2, just noticeable with argon/15% CO_2 and absent thereafter with increasing CO_2. The absence of undercut and good bead shape with the mixtures is noteworthy. There was no significant difference in any of the results when oxygen was substituted for CO_2 in amounts up to 5%.

Droplet transfer rate

The investigation on this aspect was done by using high-speed cinematography and oscillographic examination of the variation in arc voltage caused by the detachment of a droplet. A selection of the results obtained is given in Fig. 2. For all the argon/CO_2 mixtures, with or without oxygen, the mode of metal transfer at lower currents was globular as with CO_2 but the transfer rate was higher, increasing with reduction in the percentage of CO_2. As with the bead shape tests, there was no difference in the results when oxygen was substituted for CO_2 in amounts up to 5%.



2—*Droplet transfer rate*

At currents in the region of 440 amp for $\frac{1}{16}$ in. electrode and 220 amp for $\frac{1}{32}$ in. electrode a marked change in the mode of metal transfer took place. The electrode tip became tapered and the metal streamed off at a high rate. The onset of this type of metal transfer was affected by the value of arc voltage as well as arc current. With both sizes of electrode it was difficult to arrive at any reliable figure for the droplet transfer rate under these conditions but it was extremely high.

In dip transfer welding the frequency of metal transfer is the same as the short-circuit frequency and this did not alter greatly with gas mixture.

Spatter and vaporization loss

The total metal loss was determined by depositing a bead on a previously weighed plate, all but the immediate weld zone being protected from the adherence of spatter by adhesive glass fibre tape. This tape was removed after depositing the bead and before the plates were re-weighed. A $\frac{1}{16}$ in. electrode was used with a fairly long arc to give conditions of high loss.

There was no appreciable alteration in metal loss with change in gas mixture, the general level being rather higher than with argon/O_2. In dip transfer welding also there was no significant change in metal loss with change in gas mixture.

Fillet weld tests

Horizontal-vertical fillet welds were selected for practical comparative tests because they are so widely used in practice and because differences in weld profile and finish can be more readily detected than with butt welds.

On 16 s.w.g. plate using $\frac{1}{32}$ in. dia. wire with dip transfer, it was established that optimum results were obtained with rather lower arc voltages than with CO_2, the significance of this being discussed later. Differences in performance between the different gas mixtures were almost negligible although some increase in surface ripple was apparent with mixtures containing more than 20% CO_2 and oxygen.

On heavier plate $\frac{5}{16}$ in. leg length fillets were made

with $\frac{1}{16}$ in. wire at 350 amp (globular transfer). As with the fillets on 16 s.w.g. plate there was no real difference in performance with any of the seven gas mixtures.

Weld soundness

During the course of this investigation to study the effects of shielding gas composition on welding properties and weld quality, a large number of welds were examined radiographically for soundness. With a few exceptions, where conditions were known to be abnormal, most welds produced were of a very high standard, easily meeting Class 1 requirements, and in no instance did porosity occur to any level which was unacceptable compared with the results obtainable from good quality BS.1719 Class 2XX and 3XX manual electrodes.

The welds examined were made under both dip and spray transfer conditions and included bead-on-plate, sheet metal fillets, and flat and positional heavy butts.

Comparison of 80% Argon/20% CO_2 Mixtures with CO_2 and Argon/O_2 Gases

The differences in welding performance of the various gas mixtures tested were marginal but on balance the mixture giving the best all round performance was one containing between 20 and 25% CO_2, mainly because of the absence of finger-type penetration which was still found to occur with mixtures containing a lesser percentage of CO_2 (*see* Fig. 1). No advantages were found in separate additions of oxygen.

An 80/20 mixture was selected as representative of the preferred range, and used for more detailed comparison with CO_2 and argon/O_2. The essential results of these tests are discussed below.

Advantages of different penetration shape

The pronounced finger-type penetration associated with the use of argon shielding under welding conditions giving spray transfer has two disadvantages. Firstly, the rapid freezing of the metal in the tip of the finger sometimes leads to entrapment of a gas pore and, secondly, it can lead to lack of side wall fusion unless the joint is accurately prepared and the electrode correctly positioned.

With CO_2 shielding the penetration is wider at the root but is frequently too narrow at the surface of the weld because of the necessity for a low arc voltage to prevent excessive spatter. A weld penetration shape which is narrower at the surface than at the root leads to a greater risk of hot cracking in the centre of the weld.

The penetration shape obtained with the 80/20 gas mixture does not have the worst of the features given by either argon/O_2 or CO_2 and has a satisfactory triangular shape (*see* Fig. 1).

Mode of metal transfer

There are three principal modes of metal transfer with gas-shielded bare-wire welding of mild steel.

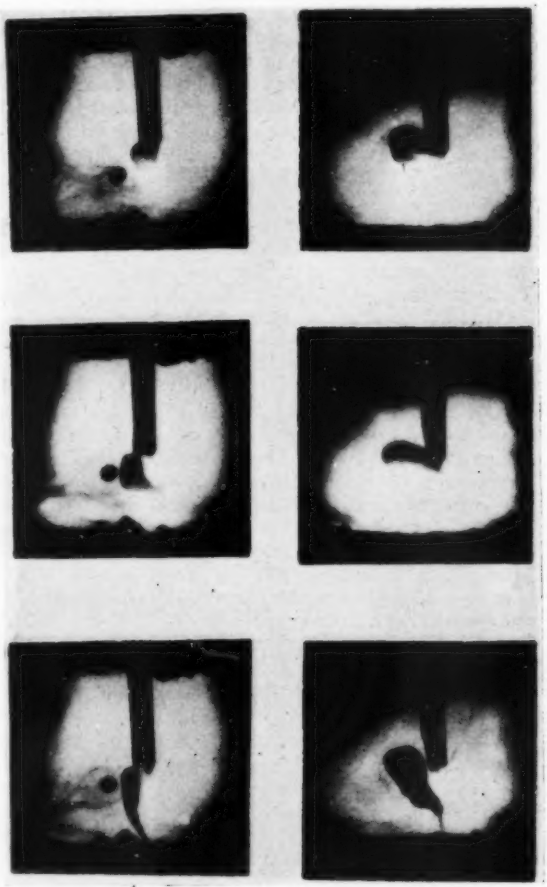
Dip transfer

With suitably designed power sources and with low arc voltages, a short-circuiting arc[2] can be maintained having a frequency up to about 100 per second.

The smoothest weld finish at maximum welding speeds is normally associated with a high frequency of short circuits. This frequency increases as the arc voltage is reduced and this helps to explain the improved results obtainable on sheet metal welding with the 80/20 mixture, as it is generally possible to weld at an arc voltage 2–3 V lower than with CO_2 under comparable conditions. If CO_2 is used at this reduced voltage, stubbing occurs. The importance of this is that for a given thickness of plate it is possible to increase the welding current and thus the deposition rate without increase in total heat input.

Globular Transfer

With CO_2 and argon/CO_2 mixtures the mode of metal transfer changes, as the current and voltage are increased, from dip transfer to a form in which individual globules of metal move in free flight from the electrode tip to the weld pool. The frequency of transfer varies from approximately 10 to 60 globules per second. Figure 3 is a reproduction of single frames from high-speed films showing typical globule shapes for the 80/20 mixture and CO_2.



(a) (b)

3—*High-speed photographs of metal transfer (globular range)—Current approx. 370 amp:* (a) *80/20 argon/CO_2;* (b) *CO_2*

The high-speed films from which these frames are taken show clearly that there is a force in the arc zone which resists the gravitational force in the molten metal globule while it is still attached to the electrode. This opposing force is not apparent when argon is used as the shielding gas, and Defize and Van der Willigen[5] attribute this to the fact that, even below the transition current, the arc plasma completely surrounds the globule and thus the upward arc pressure which is present acts on the electrode rather than on the globule. The magnitude of this force apparently becomes greater as the percentage of CO_2 in the shielding gas rises from 15 to 100%. This fact may partially explain the increase in spatter level which can result when CO_2 is used as the shielding gas. With CO_2 the plasma does not surround the drop and hence the upward arc pressure acts on the drop. Also, in the case of argon, Needham, Cooksey and Milner[6] have indicated that high-velocity plasma jets aid the detachment of drops and are responsible for their subsequent acceleration across the arc from the electrode tip to the workpiece.

With change in the gas shield, provided that there is no change in the restraining force due to surface tension, it is probable that variation in droplet rate at a constant current is due to a change in the plasma jet velocity associated with a particular gas. Since droplet rate is higher for argon than for CO_2 it is reasonable to assume that the plasma jet velocity is higher for the former and that for a mixture of the two gases the jet velocity and hence the transfer rate will have an intermediate value, as is the case.

It has also been suggested[7] that with CO_2 shielding an important factor in this upward force is the expansion in volume of the gas in the arc zone as it is dissociated from CO_2 to CO and O_2. During the course of this investigation high-speed films were taken of metal transfer in a mixture of two volumes of CO and one volume of O_2 to simulate a dissociated CO_2 atmosphere. These films, however, did not reveal any difference at all from the normal type of CO_2 transfer so it is doubtful if this expansion is a significant factor in the upward force on the droplet.

Spray transfer

With argon/O_2 mixtures it is well known that the form of metal transfer changes to what has been termed "spray" when the current density in the electrode exceeds a certain value—approx. 200 amp on a $\frac{1}{16}$ in. dia. wire. With spray transfer the metal streams from the tip of the electrode in a rapid succession of droplets, generally rather smaller in diameter than the electrode wire.

This type of metal transfer does not occur with CO_2 shielding even with welding currents up to 500 amp on $\frac{1}{16}$ in. and $\frac{5}{64}$ in. wires. It does occur, however, with the 80/20 mixture at the following approximate current levels for different wire diameters:

$\frac{1}{32}$ in. dia.—220 amp
$\frac{5}{64}$ in. dia.—330 amp
$\frac{1}{16}$ in. dia.—440 amp

The actual current at which transition from free flight globular to spray transfer occurs varies somewhat with arc length and other factors such as electrode extension.

Welding conditions are generally better when using spray rather than globular transfer and this accounts for the improved results obtainable with argon/CO_2 mixtures compared with CO_2 on flat position fillet and butt welds in plate $\frac{1}{4}$ in. thick and over.

Spatter and vaporization loss

Table IV gives the results of tests to determine the amount of metal loss by spatter and vaporization. These tests showed that the 80/20 mixture gave somewhat more spatter loss than argon/O_2, but a little less than CO_2 at its least. Carbon dioxide, however, is more sensitive to changes in welding conditions, particularly arc voltage, and with relatively small departures from the optimum, spatter loss can increase to as much as 17·5%.

Table IV

Spatter and vaporization loss, using $\frac{1}{16}$ in. dia. electrode

Shielding Gas	*Arc Voltage, V*	*Current Range, amp*	*Spatter and Vaporization Loss Range, %*
98/2 (argon/O_2)	30–32	360–400	1·6–2·4
80/20 (argon/CO_2)	30–32	360–470	3·4–6·6
CO_2	31–38	360–400	5·0–17·5

It is difficult to present the figures of actual spatter loss in a form which gives an accurate overall comparison. This is because the amount of spatter obtained with CO_2 shielding varies greatly depending upon the type of joint and the welding conditions. Operationally, spatter can present a major problem with CO_2 shielding particularly at currents over 250 amp. At such currents the globules of spatter tend to be quite large and consequently adhere to the plate surface more readily. Even where the spatter accumulation on the plate surface can be tolerated, it must be removed at frequent intervals from the nozzle of the welding gun to ensure an adequate coverage of shielding gas.

With the 80/20 mixture the amount of spatter is always at a lower level than with CO_2 under corresponding welding conditions and it does not normally present any problem, but in both cases severe arc blow can cause excessive spatter. Even under dip transfer conditions, where spatter with CO_2 shielding is generally at a low level, the reduced spatter accumulation on the nozzle when using the 80/20 mixture can be of distinct value when making vertical and overhead welds at currents of the order of 200 amp.

Mechanical properties and crack resistance

The mechanical properties of weld metal deposited by the 80/20 gas mixture, CO_2 and argon/O_2 were compared using three wires, E.1, E.2 and E.3. Two sizes of wire were used in each case, $\frac{1}{32}$ in. dia. with dip transfer and globular or spray transfer, and $\frac{1}{16}$ in. dia. with globular or spray transfer only. The following tests were made:

(i) All-weld-metal tensile tests in $\frac{7}{8}$ in. steel plate P.8
(ii) Single-V 60° butt welds in $\frac{3}{4}$ in. steel plate P.5
(iii) Fillet weld cracking tests in steel plates P.9, P.10 and P.11.

Table V

All-weld-metal tests to Lloyd's requirements, tested in the as-welded condition

Gas	Type of Wire	E.1	E.2		E.3		
	Size of Wire, in.	1/32	1/32	1/16	1/32	1/32	1/16
	Mode of Transfer	Dip	Globular	Globular or spray	Dip	Globular	Globular or spray
CO_2	Yield Stress, tons/sq.in.	32·1	30·2	30·4	27·7	28·9	23·7
	Max. Stress, tons/sq.in.	38·6	35·9	35·6	34·5	34·2	29·7
	Elong. on 8*D*, %	16·7	19·3	20·0	21·1	23·8	24·4
	Red. in Area, %	36·5	41·7	59·1	57·0	60·5	65·0
80/20 Argon/CO_2	Yield Stress, tons/sq.in.	37·0	33·7	30·0	30·3	28·6	25·0
	Max. Stress, tons/sq.in.	41·7	41·1	35·5	37·4	35·3	30·7
	Elong. on 8*D*, %	17·3	16·0	22·0	20·0	22·7	26·2
	Red. in Area, %	50·0	31·8	64·0	63·0	58·5	66·0
Argon/5% O_2	Yield Stress, tons/sq.in.	—	—	29·6	—	—	26·1
	Max Stress, tons/sq.in.	—	—	34·7	—	—	31·0
	Elong. on 8*D*, %	—	—	22·1	—	—	23·8
	Red. in Area, %	—	—	50·0	—	—	64·0

All-weld-metal tensile tests

All-weld-metal tensile test bars were prepared and tested in accordance with Lloyd's requirements, *i.e.*, 0·564 in. dia. test bars tested in the as-welded condition. Typical results are given in Table V.

When using the dip transfer technique to produce these relatively large test pieces it was found that the welding procedure has a marked effect on the results with both argon/CO_2 mixtures and CO_2. The principal object of the dip transfer technique is to promote rapid freezing of the weld pool, thus enabling positional welding to be done with ease. When this rapid cooling is accelerated still further by the effect of mass, or by making small passes, an unacceptable increase in tensile strength and reduction in ductility results.

Furthermore, in using such a relatively cold welding technique, care is needed to ensure fusion at the weld sides and between passes, particularly when making welds in the flat position as opposed to positional welding. When welding on a cold mass, especially with small runs, these difficulties are increased. Not unexpectedly it was found that the best mechanical test results are obtained by decreasing the cooling rate by making relatively heavy passes, *e.g.*, by using a weaving technique; this procedure is also that most likely to be used in practice for vertical and overhead welding. It was also found to be advantageous to increase the arc voltage by 1–2 V over the value that gives the optimum welding performance in order to reduce the possibility of obtaining cold laps. This slight increase in voltage is necessary with both 80/20 argon/CO_2 mixtures and CO_2, but the actual usable arc voltages with 80/20 argon/CO_2 remain lower than with CO_2.

These factors were taken into account in preparing the test pieces referred to in Table V, and radiographic examination was made to ensure that the welds tested were free of the defects mentioned.

Butt weld tests

Single-V multi-pass butt welds were prepared to obtain longitudinal tensometer, transverse bend, transverse tensile tests and transverse Charpy test pieces.

The butt weld tensometer specimens were machined to Hounsfield Drawing No. 14 ($\frac{1}{20}$ sq.in.) and tested in the as-welded condition. Results are given in Table VI.

The bend test specimens were bent over a former diameter 3*T* with both the root and face of the weld in tension, in accordance with the previsions of BS.639: 1952.

The transverse tensile test pieces were also prepared to BS.639:1952 and tested in the as-welded condition.

The 10 mm Charpy specimens were machined and tested in accordance with BS.131, Part 2:1959, with the notch in the outer face of the weld, longitudinal with the seam. Results are given in Table VII.

As with the all-weld-metal tests each butt weld was radiographed before being tested.

Table VI

Hounsfield tensometer test pieces ($\frac{1}{20}$ sq.in.), tested in the as-welded condition

Gas	Type of Wire	E.1	E.2	E.3	
	Size of Wire, in.	1/32	1/16	1/32	1/16
	Mode of Transfer	Dip	Globular or spray	Globular or spray	Globular or spray
CO_2	Yield Stress, tons/sq.in.	39·6	26·4	25·2	25·2
	Max. Stress, tons/sq.in.	44·0	34·4	32·4	31·5
	Elong. on 3·54*D*, %	25·0	27·0	36·0	35·0
	Red. in Area, %	58·0	55·0	50·0	64·0
80/20 Argon/CO_2	Yield Stress, tons/sq.in.	38·0	30·5	26·0	30·0
	Max. Stress, tons/sq.in.	42·8	35·9	34·0	35·2
	Elong. on 3·54*D*, %	23·0	30·0	33·0	29·5
Argon/5% O_2	Red. in Area, %	45·0	66·0	64·0	62·0
	Yield Stress, tons/sq.in.	—	31·2	—	23·7
	Max. Stress, tons/sq.in.	—	36·8	—	30·4
	Elong. on 3·54*D*, %	—	28·0	—	35·0
	Red. in Area, %	—	65·0	—	70·0

Table VII

Charpy tests on butt welds (average of three results)

Gas	*Type of Wire* / *Size of Wire, in.* / *Mode of Transfer*	*E.1* $\frac{1}{32}$ *Dip*	*E.2* $\frac{1}{16}$ *Globular or spray*	*E.3* $\frac{1}{32}$ *Dip*	*E.3* $\frac{1}{16}$ *Globular or spray*
CO_2	Room temp. (18°C.)	88·4	39·0	73·3	61·9
	—10°C.	44·6	23·3	40·7	54·4
	—30°C.	29·2	11·8	31·5	30·1
80/20 Argon/CO_2	Room temp. (18°C.)	62·8	70·7	81·6	93·7
	—10°C.	36·9	51·4	72·3	50·6
	—30°C.	27·6	39·4	55·2	27·9
Argon/5% O_2	Room temp. (18°C.)	—	74·5	—	59·8
	—10°C.	—	42·1	—	33·3
	—30°C.	—	41·7	—	22·1

Fillet weld cracking tests

The results obtained on a limited range of selected carbon steels are given in Table VIII. The method of testing was generally to BS.639:1952, *i.e.*, by making restraining welds of a controlled size followed by the test weld within 5–7 sec of the restraining welds. Conditions were adjusted so that a standard argon/O_2 shielded weld was on the borderline of cracking, and the tests on the other gases were then made with a similar procedure.

Discussion of results of mechanical tests

All-weld-metal tensile tests

The figures given in Table V show that the mechanical properties of welds made under argon/CO_2 shielding are generally similar to those made under argon or CO_2.

A number of fractured test specimens welded with $\frac{1}{32}$ in. wires and both CO_2 and argon/CO_2 shielding, have shown 'haloes' on the fracture faces. These have occurred more frequently when using dip transfer, even when making comparatively heavy runs. Undoubtedly the haloes have contributed towards a lowering of ductility. With wire E.1, which produces welds having high maximum stress, this reduction in ductility has been sufficient to bring the value below the minimum requirement of 18% over 8*D*. With wire E.3, however, fully satisfactory ductility was obtained with dip transfer using either 80/20 argon/CO_2 mixture or CO_2 for shielding.

Investigations into the fundamental causes of the occurrence of haloes are still in progress, but it seems that they are associated with the entrapment of gas in very tiny pores, most of which are not visible by normal radiographic means. This entrapment of gases seems to be more likely when the weld pool cools rapidly, as when using fine wires for welding heavy plate.

No haloes have been observed when using $\frac{1}{16}$ in. wire with globular or spray transfer.

Butt weld tensometer tests

The results are generally similar to those of the all-weld-metal tensile tests, *i.e.*, all have a satisfactory minimum elongation exceeding 25% over 3·54*D* except E.1 wire with dip transfer. In general the results with 80/20 argon/CO_2 mixture are equal to those with CO_2 and argon/O_2. Some haloes were again noted, principally with dip transfer welding.

Butt weld bend tests

All the specimens were bent through 180° without failure, although some of the dip transfer specimens, both with CO_2 and argon/CO_2 mixtures, showed some extremely fine porosity on the surface after bending. This no doubt was another reflection of the condition producing the haloes already referred to. The welds made with globular or spray transfer were all sound.

Transverse tensile tests

Because the yield point and ultimate tensile strength of the parent plate at 16·7 and 26·9 tons/sq.in. respectively were lower than that of the weld metal, all failures took place in the plate away from the weld.

Butt weld Charpy tests

The results of these tests indicate that the impact properties of welds made with 80/20 argon/CO_2 mixtures are generally similar to those of CO_2 or argon/O_2 shielded welds and easily satisfy the requirements of BS.639:1952, Amendment No. 2, 1959.

Fillet weld cracking tests

The short series of tests done indicates that welds made with 80/20 argon/CO_2 mixture have a crack resistance at least as good as that of CO_2 shielded welds. Indeed, because of the more desirable shape of the penetration bend it is expected that on many applications there would be less danger of cracking than with either CO_2 or argon/O_2.

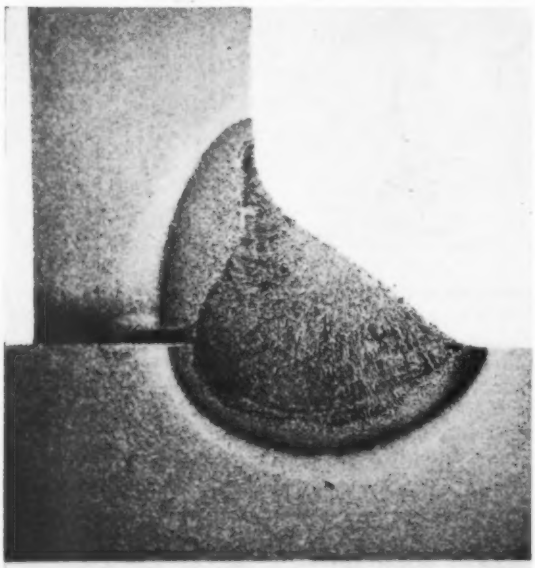
Table VIII

Fillet weld cracking tests ($\frac{1}{16}$ in. dia. wire, 350 amp)

Plate	*Wire* / *Gas*	*Argon/5% O_2*	*E.2* *CO_2*	*80/20 Argon/CO_2*	*Argon/5% O_2*	*E.3* *CO_2*	*80/20 Argon/CO_2*
P.9		Crater only	Nil	Nil	Nil	Nil	Crater only
P.10		Nil	Crater only	Crater only	Crater only	Crater only	Crater only
P.11		25	30	30	30	25	30

Weld soundness

When comparing welds made in argon/CO_2 mixtures with those using CO_2 only it was found that welds of equal soundness were obtained when the appropriate welding conditions were used in each case. Generally it was also found that the welding conditions are less critical than when using argon/O_2.



4—Macrograph of $\frac{5}{16}$ in. leg horizontal-vertical fillet welded with $\frac{3}{64}$ in. dia. wire at 350 amp, 31 V, 15 in./min, 80/20 argon/CO_2

Practical Aspects of the Use of 80/20 Argon/CO_2 Mixture

The foregoing sections have been mainly concerned with the evaluation of the technical features of mixtures and it is now of interest to consider the more practical aspects.

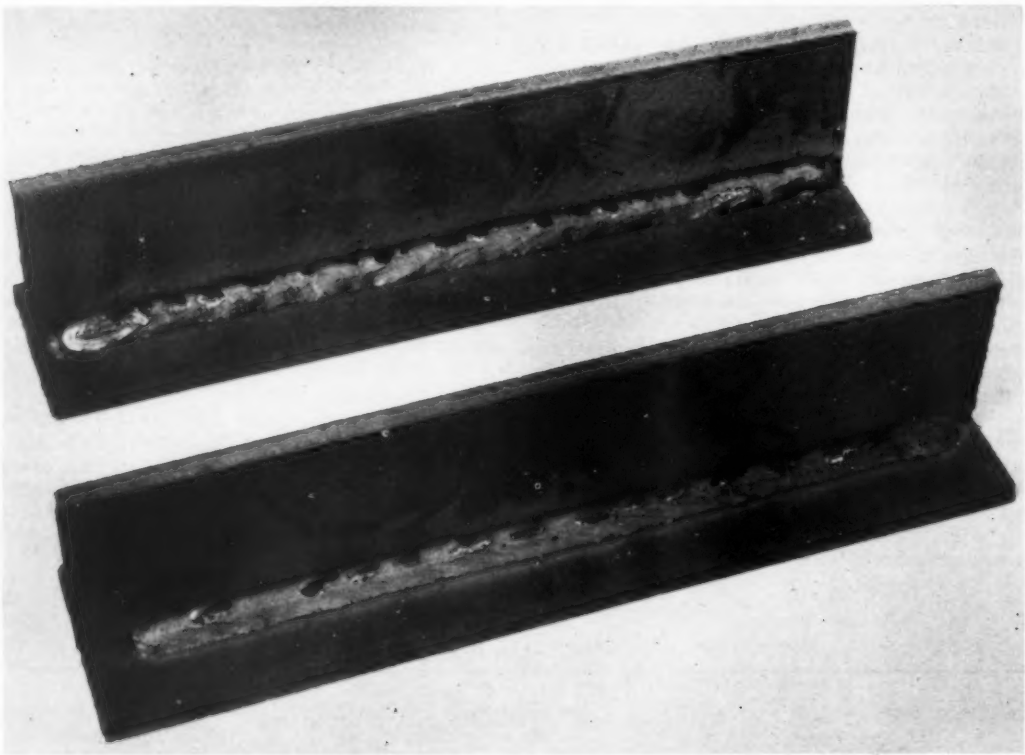
Semi-automatic welding

Flat position welding with globular or spray transfer

Because of the known advantages of spray transfer, the current ranges used with the 80/20 mixture were principally confined to those giving this type of metal transfer.

Using $\frac{1}{16}$ in. wire at 450 amp for horizontal-vertical fillets it was found that the weld pool was too hot and the weld metal too fluid for the welder to control readily. This current could however be used for flat position butt welds in prepared joints in heavy plate.

With $\frac{3}{64}$ in. wire it was found that at a current of approx. 350 amp it was possible to exercise good control over the molten weld metal and to make both butt and fillet welds in plate $\frac{1}{4}$ in. thick and over without difficulty. Cross sections from horizontal-vertical fillet welds of $\frac{1}{4}$–$\frac{5}{16}$ in. leg length showed a



5—Comparison of horizontal-vertical fillets welded with $\frac{3}{64}$ in. dia. wire using: (a) *350 amp with 80/20 argon/CO_2;* (b) *300 amp with CO_2*

very good penetration shape (Fig. 4) with full fusion $\frac{1}{8}$–$\frac{3}{16}$ in. beyond the root of the joint. The weld profile was of a good shape with no sign of undercut (Figs. 4 and 5). Under these conditions the welding speed with 80/20 argon/CO_2 mixture on horizontal-vertical fillet welds is 25% greater than with argon/O_2 shielding using $\frac{1}{16}$ in. wire at 330 amp. Penetration is also greater so that the strength of the weld for a given fillet leg length is increased. Ease of welding and resultant weld finish were found to be very similar.

With CO_2 shielding it has been found necessary to restrict the welding current to approx. 300 amp on $\frac{3}{64}$ in. dia. wire to permit proper control of the fluid weld metal for horizontal-vertical fillets. A comparison between fillets made with CO_2 and the 80/20 mixture is shown in Fig. 5. With higher currents on $\frac{3}{64}$ in. or larger wires, the weld metal tends to fall to the bottom leg of the fillet and spatter is increased.

Sheet metal welding using dip transfer

The ease with which sheet steel down to 20 s.w.g. can be welded with the bare-wire gas-shielded process has greatly attracted many fabricators, and this is becoming an important field for the process. With CO_2 shielding the maximum welding speed is usually determined by the acceptability of the weld finish. This deteriorates, with a tendency for cold lapping at the edge of the weld and with increased spatter, as the welding current and speed are increased beyond certain limits. With the 80/20 mixture the best welding conditions are obtained using an arc voltage some 2–3 V lower than that used with CO_2 shielding. A lower arc voltage increases the frequency of short circuits and this may partially explain the superior wetting action obtained at high welding speeds on thin plate material. This superior wetting action makes it possible to deposit smaller, neater fillets on light gauge sheet than can be obtained with CO_2 shielding. As already explained on p. 154, the lower arc voltage also leads to faster deposition rates.

To make a more precise comparison than is possible with manually operated equipment, a self-contained gun was mounted on a tractor so that the welding speeds could be accurately measured. A series of fillet welds in 16 s.w.g. sheet was made at speeds varying from 20 to 52 in./min using $\frac{1}{32}$ in. dia. wire. Figure 6 illustrates two welds made at 48 in./min, one with CO_2 shielding and the other with the 80/20 mixture. At this welding speed, the difference in finish is clearly apparent. With CO_2 shielding it was found necessary to reduce the welding speed by approx. one-third to 32 in./min to achieve a finish comparable to that obtained with the 80/20 mixture.

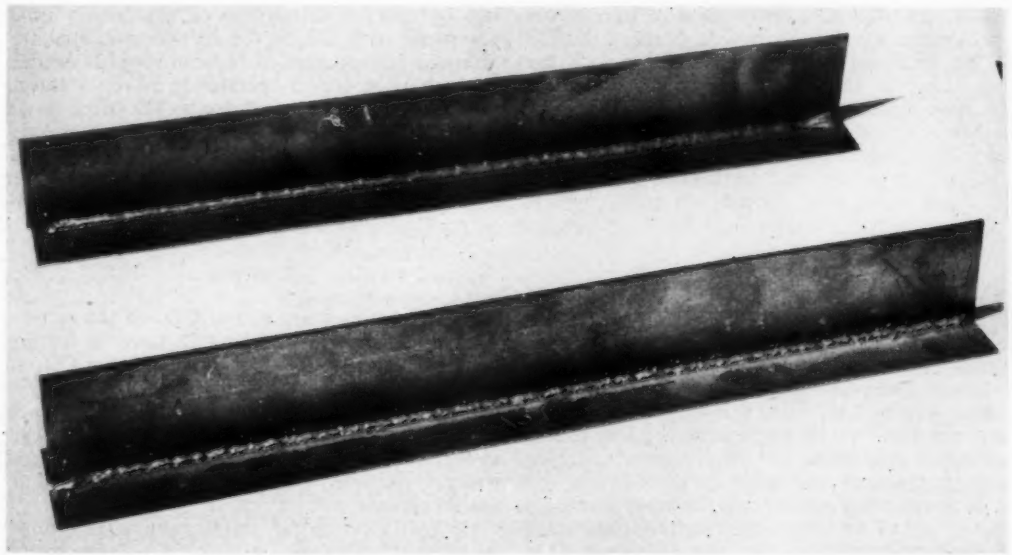
All-position welding using dip transfer

Butt welds in $\frac{3}{4}$ in. thick plate and in $\frac{3}{8}$ in. wall thickness pipe were made to compare the performance of argon/CO_2 with CO_2 shielding.

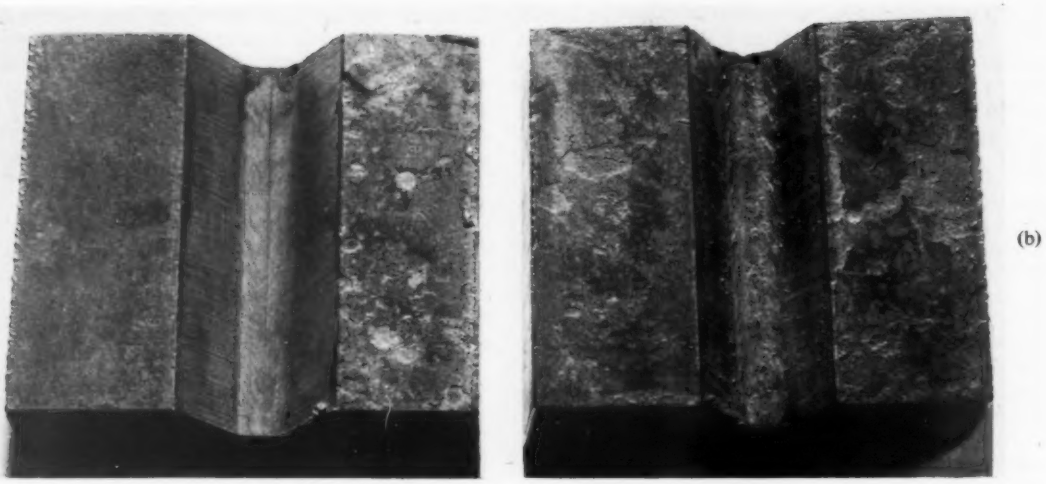
At similar welding currents the finish of the welds obtained with argon/CO_2 was rather smoother and less rippled than those with CO_2. This improvement was accompanied by some reduction in spatter accumulation on the nozzle of the welding gun when operating at the maximum usable currents, *i.e.*, 160–200 amp. At these currents the deposition rate is 6–7 lb/hr, which is approximately double that obtainable with 6 s.w.g. Class 3XX BS.1719 electrodes on vertical welds.

Fully automatic welding

The principal use of the CO_2-shielded bare-wire process up to the present time has been for fully automatic welding of plate varying from approx. 12 s.w.g. to $\frac{1}{4}$ in. For a number of applications an acceptable weld finish can be obtained at exceptionally high speeds. Argon/CO_2 mixtures do not give any significant improvement on such applications.



6—*Fillet welds in 16 s.w.g. mild steel at 120 amp, 48 in./min:* (a) *With 80/20 argon/CO_2;* (b) *with CO_2. (This speed is too high for CO_2 shielding, giving excess spatter and cold lapping at the weld edges)*



7—Comparison of root runs in 1 in. deep 60° V, using $\frac{1}{16}$ in. dia. wire at 430 amp, 10 in./min: (a) *With 80/20 argon/CO_2:* (b) *with CO_2*

Bare-wire gas-shielded welding does not compete successfully with automatic flux-using processes on heavier plate because much higher welding currents can be used with the latter processes. Nevertheless there are occasions when welding in awkward joints where it is a distinct advantage to use a process that is free from slag. On such applications the excellent bead formation, smooth finish, and freedom from spatter obtained with argon/CO_2 shielding can be advantageous. A typical root run in a V joint compared with a similar weld with CO_2 shielding is shown in Fig. 7. Both runs were made with $\frac{1}{16}$ in. wire at a current of 450 amp.

Health considerations

In common with any welding process employing CO_2 in the shielding gas, dissociation of CO_2 occurs giving oxygen and carbon monoxide. Some of this CO leaves the arc zone without recombining with the oxygen. However, tests with an 80/20 argon/CO_2 mixture have shown that the level of CO near the arc is less than that in CO_2 shielded welding and that the welder inhales less than the maximum permissible limit of 100 v.p.m.[8] even assuming a duty cycle of 100%. These tests were carried out using natural ventilation under the conditions laid down in American Standard Z.49.1–1958.[9]

Economic aspects

The economic evaluation of a welding process on the basis of a number of welds made under laboratory conditions is extremely difficult. Variations in duty cycle, labour rates, and the method of allocation of overheads alone make comparison difficult, and laboratory control of weld preparations and procedure means that the results will not always compare reliably with practical conditions.

The work described in this paper, however, indicates certain features of the argon/CO_2 mixtures that must lead to savings in welding costs compared with CO_2 shielding.

On sheet metal using dip transfer the 2–3 V lower arc voltage enables higher currents to be used without overheating. It is also possible to make smaller and neater fillets, and the combined effects of these two features is a gain of 25–50% in welding speed and a saving of up to 25% of wire.

In horizontal-vertical fillet welding of thicker plate with spray transfer it is possible to use 15–20% higher current with argon/CO_2 mixtures than with CO_2. The gain in welding speed to be expected from this, however, can be largely offset by using longer nozzle-to-plate distances and hence more I^2R heating with CO_2. With the argon/CO_2 mixtures it is not possible to take advantage of I^2R heating, because the weld pool, when using the highest practicable welding current, is already at the maximum size and temperature that can be handled satisfactorily. The outstanding operational advantage of argon/CO_2 mixtures compared with CO_2 is the reduction in spatter, and although no apparent increase in speed is available it is much easier for an operator to establish and maintain good welding conditions. The time saved in setting up and in cleaning spatter from the nozzle and workpiece thus gives a noticeably higher overall output, and indeed such savings often prove more important in increasing output than deposition rate by itself.

Conclusions

(1) Mixtures of argon and CO_2 in the range containing between 15 and 25% CO_2 have the feature not possessed effectively by either argon/O_2 or CO_2 alone, that they can give either spray or dip transfer by choice of appropriate conditions. Argon shielding gives good spray transfer, but dip transfer welding of steel is not practicable. CO_2 shielding gives a good dip transfer, but spray transfer cannot be obtained at any usable current.

(2) With dip transfer, stable welding conditions can be obtained at an arc voltage 2–3 V lower than with CO_2, and this leads to faster welding speeds in sheet metal work.

With spray transfer, stable welding conditions can be obtained at higher currents than with argon/O_2.

Both these features lead to higher welding speeds.

(3) Mixtures containing between 20 and 25% CO_2 give a penetration shape avoiding the finger-type penetration of argon, with its risk of root cavities and the deep and narrow penetration of CO_2 with its susceptibility to cracking.

(4) The mixture having the best overall combination of properties is one containing 75–80% argon and 15–20% CO_2. There are no advantages from a ternary mixture containing oxygen.

(5) An argon/CO_2 mixture in the above range offers definite economic advantages compared with CO_2 in the welding of sheet metal, and definite operational advantages in welding material $\frac{1}{2}$ in. thick and above, a gain which will make the use of a more expensive gas worthwhile. The mixture is more economic in all applications than argon/O_2 shielded welding.

None of the gas-shielded bare-wire processes compete economically with the fully automatic flux-using processes owing to the much higher currents that can be used with the latter on plate $\frac{1}{4}$ in. thick and over.

(6) Using the correct combination of wire, shielding gas, and welding conditions, the radiographic soundness and mechanical properties of welds made with the 80/20 argon/CO_2 mixture will meet Lloyd's Class 1 requirements.

Acknowledgment

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An Adhesion Test for Aluminium Spray Coatings and other Metallized Surfaces

By R. S. Smith and N. Stephenson, B.MET., PH.D.

A steel button is bonded to the metallized surface with a synthetic resin and the coating immediately adjacent to the button is trepanned. The tensile force required to detach the known area of deposit is measured. Based on this laboratory-developed method an adhesion-measuring instrument was designed for use in the field.

The laboratory techniques which use cold-curing or hot-curing resins are applicable to a number of metals sprayed on grit-blasted mild steel plates, but the scope of the field test is restricted mainly by the limited strength of the available cold-curing synthetic adhesives. Thus adhesion may be measured under field conditions when the bond strength of spray deposits does not exceed that of aluminium-spray coatings on grit-blasted mild steel. Subject to similar limitations the test enables cohesion of thick deposits to be measured. Adaptation to non-destructive or semi-destructive tests is possible under some circumstances.

Introduction

IN RECENT years aluminium-spray coatings have become increasingly popular for the protection of steelwork against corrosion in marine or industrial atmospheres. On large structures the process consists of preparation of the surface by grit-blasting followed by deposition of commercially pure aluminium from spray guns fed with wire or powdered metal. Coating thicknesses of 0·004–0·010 in. are usual but greater thicknesses may be applied for special conditions of service. The aluminium layer is slightly porous and, although in service it is capable of protecting the steel,

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the protective action frequently is supplemented by the additional application of sealing paints. These tend to penetrate the pores of the coating, thereby restricting the access of corrosive media and slowing down the sacrificial loss of the aluminium. The pores provide an excellent key for the sealing paint, so that the sprayed metal and the paint are complementary. If the coating is damaged mechanically, the electrochemical effect between aluminium and steel prevents penetration of corrosion along the interface. In the absence of a sealing paint the pores are progressively filled with corrosion products of aluminium, and this is said to be partly responsible for the protection afforded by spray-aluminized coatings.

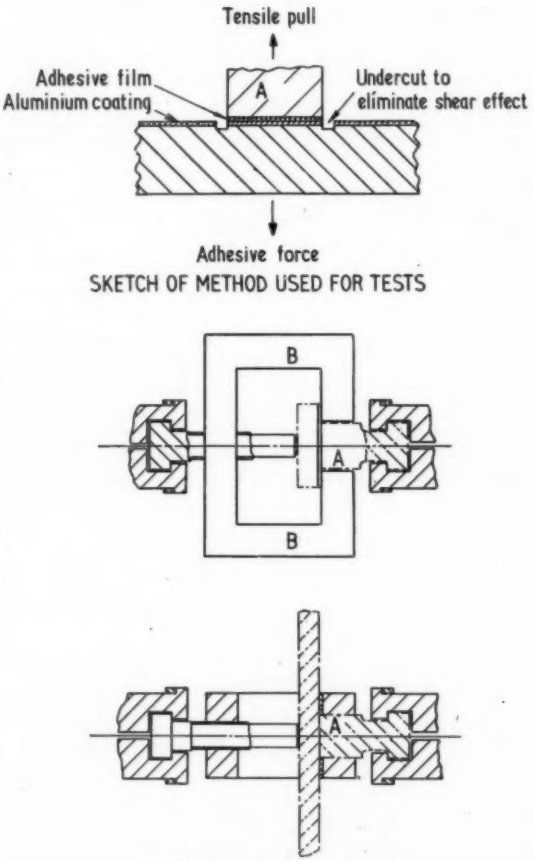
The scientific literature on metallizing seems to be by no means extensive, although considerable practical experience is recorded. This may be ascribed, at least in part, to the paucity of simple quantitative techniques of measurement. In particular, there appears to be no simple method of determining numerically the adhesion of spray coatings on site. Thus, quantitative investigation of the effect on adhesion of process and service variables has been difficult. Fairly accurate techniques for measurement of adhesion have been reported in the literature[1,2,3] but these require precisely machined test pieces, or they are applicable only to very thick coatings, or they cannot be used outside the laboratory. Qualitative tests have been described, such as the "scribe" test set out in BS.2569, the response to chipping with pneumatic tools, or attempting to peel the coating with adhesive tapes. The ease with which a coating can be chipped, peeled, or lifted by inserting a knife blade at the interface is no real criterion of adhesion because this facility is dependent on coating thickness and strength.

Ferguson and Tsao[4] proposed to measure the adhesion in tension of electroplated metals by making use of relatively high strength synthetic adhesives. They intended to stick metal 'handles' on to the electroplate and to measure the force needed to pull away the coating in a direction perpendicular to the plated surface. The adhesives appeared to depend on solvent evaporation, and the attempt seems to have been frustrated by entrapped bubbles at the smooth metal joints which led to variable strength. No electroplated coatings were tested. McDermott[3] used hot-curing polyethylene to bond a grit-blasted button to a similar metal-sprayed button; the assembly was pulled in a tensile testing machine and, in this way, the adhesion of spray coatings of tin, zinc, aluminium, bronze, copper, steel, and lead coatings respectively, applied by the powder process, was determined. The advent of strong cold-curing adhesives and the availability of hot-curing synthetic resins of enhanced strength has led, in the present work, to the further development of this type of adhesion test.

Laboratory Test

The principle of the test is illustrated in Fig. 1. A steel 'button' *A*, freshly grit-blasted at the end, was bonded to the spray coating using a synthetic resin. The coating was cut through by means of a tubular trepanning tool (not shown) around the button so as to prevent the shear strength of the coating and the strength of the resin fillet from contributing to the measured adhesion. The force in tons needed to part the coating from the steel was measured in a tensile testing machine fitted with a bridge assembly *B*. Since the area of coating to be removed was chosen arbitrarily at 1 sq.in., numerically the force was the tensile adhesive strength of the coating in tons/sq.in. On completion of the test the adhesive was de-natured by heating it for a short time at 400°C., after which the disc of detached coating could be removed from the button. It was shown that, if the adhesive is adequately de-natured, this disc can be used for direct measurement of the coating thickness for comparison with values previously obtained with a thickness meter.

The adhesive mostly used in the trials was a cold-curing poly-ester resin, and the proportions of resin, accelerator and catalyst were adjusted to give complete curing overnight. In some instances a thixotropic agent was added to prevent undue penetration of the adhesive through pores in the coating, but metallographic examination showed that this was not necessary for coatings thicker than 0·005 in. Another cold-curing adhesive became available later, and has since been used extensively in laboratory and field trials. This synthetic resin required no addition of thixotropic agent, and penetration into aluminium spray coatings was found to be less than 0·0015 in. Other



1—*Laboratory test for adhesion*

adhesives were tried, and it was found that those depending on solvents were unreliable; the coatings were 'torn' away at unduly low stresses. A similar effect was encountered with incompletely cured poly-ester resin. Hot-curing epoxy-resins were used when the strength of the poly-ester adhesive was inadequate, and additional tests indicated that the curing temperatures in the range 120° –180°C. had no appreciable effect on the adhesion to aluminium-spray coatings. Thus the time needed to complete the test could be diminished if necessary by using the hot-curing epoxy-resin or by warm-curing the poly-ester adhesive. It was important to cool the assembly to room temperature before measuring the adhesion. All adhesives were ineffective when sealing paints were present; either the resin did not adhere to the coating because it could no longer penetrate superficially or, particularly for the poly-ester resin, the measured adhesion was extremely low in comparison with values determined before applying the sealing paint. Since it was unlikely that sealing paints affected the adhesion at the aluminium/steel interface a possible explanation is that the paints inhibited full curing of the resin over most of the area concerned. Thus, only part of the coating adhered and, on applying the load, the coating was lifted at these points, while the remainder of the resin deformed plastically and the metal deposits were torn away at low load. Details of suitable adhesives are given in the Appendix.

To provide an indication of the reproducibility of the test, repeated determinations of adhesion were made for sprayed aluminium coatings on each of three steel plates, using the cold-curing poly-ester adhesive. The coatings were nominally 0·010 in. thick on plate approx. 3 in. × ½ in. section. In all adhesion tests the area of coating removed was 1 sq.in. The plates were prepared by grit-blasting with 24 mesh angular chilled iron grit in accordance with BS.2569, Part I; 1955, using air pressure of 70 lb/sq.in. (suction method). After grit-blasting, they were immediately sprayed with aluminium, using a proprietary wire-fed oxy-propane gun. The oxygen, propane, and air pressures respectively were 24, 25 and 65 lb/sq.in. The aluminium wire was ⅛ in. dia. (better than 99·7% purity), and was consumed at the rate of 7 ft/min approximately. The results are given in Table I. The mean value of 0·42 tons/sq.in. was in reasonable agreement with a value of 0·46 tons/sq.in. obtained elsewhere[2] by a similar spraying procedure but with a different testing technique.

Although the present test was developed primarily to determine the adhesion of aluminium-spray coatings it might be suitable for other metallized deposits.

Table I

Reproducibility of adhesion for aluminium-spray coating on grit-blasted mild steel

Sequence of Test	*Adhesion, tons/sq.in.*		
	Plate A	*Plate B*	*Plate C*
1	0·37	0·45	0·42
2	0·31	0·30	0·60
3	0·52	0·36	—
4	0·43	0·50	0·44
5	0·30	0·37	0·62
6	0·31	0·44	0·40

Table II

Adhesion of miscellaneous coatings
(All coatings nominally 0·010 in. thick)

Coating	*Adhesion, tons/sq.in.*	
	Wire Process	*Powder Process*
Aluminium	0·47 C.(69)	0·74 C.F. 0·58 H
Zinc	0·34 C.D.	0·26 C. 0·30 H.
Copper	0·45 D.	—
Steel	0·71 C.F. 1·31 R.D.	0·55 C.F. 0·86 R.
Ni–20% Cr	1·41 H.	—
Nickel	0·57 C.F. 1·12 H. 1·07 H.	0·48 C.F.

C—cold-curing poly-ester resin
H—hot-curing epoxy-resin
R—hot-curing resin bonded under pressure
F—resin failed
D—coating delaminated
(69)—mean of 69 tests

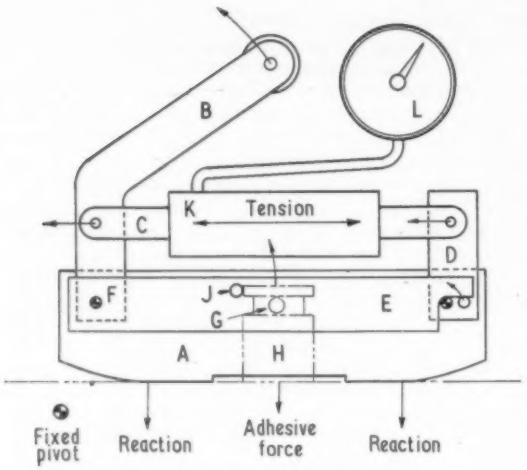
Thus Table II shows the adhesion of aluminium, zinc, nickel, or steel coatings sprayed by the wire or powder processes, and of copper or Ni–20% Cr sprayed by the wire process on to grit-blasted mild steel plates. Each of the deposits was nominally 0·010 in. thick. For some coatings the strength of the cold-curing poly-ester resin was inadequate, but these usually could be tested using the epoxy-resin hot-cured at 190°C. for 3 hr. Exceptions were the sprayed steel coatings which responded only to another epoxy-resin hot-cured under pressure. The steel and zinc coatings deposited by the wire process were delaminated during measurement of adhesion; their adhesive strength exceeded the cohesive strength. Hence the test also should be useful in proving the cohesive strength of sprayed metal coatings. Where adhesives are insufficiently strong to permit detachment or rupture of the coatings the test should give a useful measurement of minimum adhesion and cohesion.

Occasionally there was failure to detach the whole of the coating from the circular area under test although part of the underlying steel surface was uncovered. Under these conditions inadequate coverage with resin or the presence of entrapped air bubbles were suspected if the measured load was abnormally low. On the other hand, if the failure occurred at normal or high loads, either the strength of the resin joint or the adhesion of the spray coating to the steel was non-uniform. Non-uniformity in the adhesion of aluminium deposits has been demonstrated elsewhere.[5]

The technique might not be readily applicable to thin electro-deposits because their smooth surfaces cannot be roughened satisfactorily to provide adequate keying for the adhesive. Thus, using the cold-curing resin on a 0·0005 in. thick nickel plate, electro-deposited directly on to a machine-ground mild steel surface from a Watts-type bath, it was found that failure occurred in the resin at a stress of 0·16 tons/sq.in., hence the adhesion of the nickel plate must have exceeded this value.

Field Test

It would clearly be desirable for the techniques described to be applied directly to large components



2—Principle of lever adhesion tester

and structures. There was no major problem in bonding the steel buttons to the coating, or in trepanning the coating around the button. For curved surfaces, the working face of the button could be shaped to conform with the curvature of the coated surface, but it was found that flat buttons were suitable if the radius of curvature exceeded 12 in. The working principle of the portable instrument devised to apply and to measure the tensile force needed to detach the deposit is illustrated in Fig. 2.

Two parallel plates *A* supported a lever system *BCDE*. The arm *E* of the system consisted of two lifting bars located inside the parallel plates and supported at one end by a pivot pin *F*. Midway along their length the lifting bars were fitted with knife edges *G*, which engaged in the annular groove of the adhesion button *H*. A tie *J*, between the two lifting bars, also served to locate the knife edges correctly in the groove of the button. The link *C* of the lever system included a load-indicating device comprising a hydraulic cylinder *K*, connected to a pressure gauge *L*. Movement of the handle *B* transmitted force through the fluid in the load indicator and from there through the remainder of the lever system, to impart a substantially axial tensile load to the button. Reactive forces held the instrument to the metallized component until the coating was detached, and frictional forces prevented slip along the surface of the component. The adhesion tester was calibrated against a tensile testing machine.

The procedure when carrying out adhesion tests under field conditions was similar to that followed in the laboratory. If necessary, the metallized surfaces were lightly scratch-brushed to free them as much as possible from corrosion products or dust. Grease and moisture were removed or dispersed with petroleum ether and methylated spirit; adequate ventilation is, of course, essential when using these inflammable solvents. The buttons were cemented to the spray coating with the cold-setting poly-ester resin; a small proportion of a thixotropic agent added to the resin prevented loss of the adhesive when the coatings to be tested were not in the horizontal plane. However, the alternative cold-curing resin did not require the addition of a thixotropic agent. Large permanent magnets fitted with spring clamps were used to hold the buttons in position while the resins were curing (but it should be noted that the magnetic clamps might leave stray magnetic fields which would influence the accuracy of magnetic thickness-measuring instruments). The adhesives were allowed to cure overnight, but the curing time was dependent on temperature; in warm weather curing often was complete in 6 hr. On curved surfaces, such as those in cylindrical ducts, the deposits could be trepanned with a tubular 2-tooth cutter before engaging the test instrument with the button to complete the test.

With this instrument it was found that the adhesion of aluminium-spray coatings on mild steel plates was similar to values obtained from adjacent areas on the same specimens using the laboratory test already described. The instrument has been used to determine extensively the adhesion of aluminium-spray deposits in a system of air ducts. Table III gives examples of the type of information obtained.

Discussion

In many instances the ultimate adhesive strength of spray coatings need not be known, and it would be sufficient merely to have the assurance that the bond strength exceeds a specified value. In this case the adhesion test need not be entirely destructive. For example, adhesives having strengths inferior to that of the bond between deposit and basis metal might be used. However, the strength of joints made with adhesives often depends on factors which are not controlled readily, such as the thickness of adhesive at the joint. The difficulty was overcome with the cold-curing resins; after a proof load had been applied the resins were de-natured by heating the steel button to a sufficiently high temperature, when the button could

Table III

Examples of adhesion in a system of air ducts sprayed with aluminium

Description of Coating	*Adhesion, tons/sq.in.*	*Thickness, in.* $\times 10^{-3}$	*Condition of steel at Interface*
Coatings suspect because of appreciable rusting at the interface. The values shown suggest that adhesion was adequate.	0·48 (60%)*	8	Rusty
	0·49 (75%)	16	Rusty
	0·65 (60%)	—	Rusty
	0·71 (60%)	—	Rusty
Localized thick coating	0·12 (50%)	95	Rusty
At the edges of coatings repaired locally by re-grit-blasting and re-spraying	0·26	18	Rusty
	0·30	20+	Rusty
	0·15	—	Rusty
	0·22	—	Rusty
Heat-affected zone of a weld made outside the ductwork.			
(*a*) Over the weld	0·00	—	Rusty
(*b*) 10 in. from weld	0·33	—	Rusty
Weld seams. Welds dressed, roughened with a pneumatic tool and sprayed with molybdenum before applying the aluminium-spray coat.	0·23 (55%)	—	Clean
	0·21 (95%)	—	Clean

* Percentage of coating, 1 sq.in., removed during adhesion test; where no figure is given there was 100% removal.

be detached easily, thus leaving the coating intact with the exception of the narrow trepanned annular gap. Complete trepanning is probably unnecessary for thin coatings because the force needed to shear the deposits is small in comparison with their strength in adhesion. On the other hand, it would be desirable to cut through the excess resin around the edge of the button. In practice, steel test plates, processed together with the work may be examined in the laboratory or with the portable tester.

Adhesion exceeded cohesion when the coating was delaminated during the test; thus the ultimate cohesive strength of the coating was measured and this was also a minimum value for adhesion. If all the coating enclosed by the trepanned area was removed the ultimate adhesive strength also represented a minimum value for cohesion. In the latter case the ultimate cohesive strength of deposits thicker than approx. 0·004 in. might be determined additionally by bonding the detached deposit, still held on one face by the steel button, to a grit-blasted steel plate; the force required to split the coating would then be measured.

Slight increase in temperature diminished considerably the time needed for curing the cold-setting resins. In the laboratory these temperatures could be obtained in a drying oven, but an electrically-heated button was devised to minimize the curing time under field conditions. This hollow steel button contained a small resistance element wound on a steatite former and insulated with mica. For safe use in constructional work the heater was designed to operate at low voltages. The curing times of the poly-ester resin were reduced to less than 2 hr but a further waiting period was necessary to ensure that the assembly had cooled to ambient temperature; otherwise, abnormally low adhesion values were obtained, presumably because the cured resin was relatively soft at elevated temperatures. After testing coatings non-destructively the electrically-heated button was readily detached by increasing the electrical input until the resin was denatured. The heat loss in thick sections of coated steel prevented adequate curing of epoxy-resins. Hence it is unlikely that the heated button will be useful at present for measurement of very adherent spray coatings on site.

When used as adhesives to join grit-blasted steel surfaces or to bond buttons to very adherent coatings the synthetic resins failed in the following ranges of stress in tension:

Cold-curing poly-ester resin	0·5–1·2 tons/sq.in.
Cold-curing epoxy-resin	0·9–1·4 tons/sq.in.
Hot-curing epoxy-resin	1·5–2·8 tons/sq.in.

The maximum strength of the alternative epoxy-resin hot cured under pressure was not determined, but it should be similar or superior to that of the epoxy-resin that could be cured without pressure. The authors have not attempted to make a detailed survey of potentially suitable adhesives. Clearly, the availability or development of stronger adhesives will extend the scope of the test.

In the laboratory the adhesion test is applicable to a number of metal spray coatings on mild steel, where the steel surface has been prepared by ordinary grit-blasting techniques. Other than as a proof test, it might not be adequate for the deposits of very high adhesion obtained by coating specially prepared surfaces. In the field, where grit-blasting most frequently is the only practicable method of surface preparation, aluminium or zinc spray coatings can be tested, subject to certain limitations in the geometry of the metallized surfaces.

Acknowledgments

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APPENDIX

Details of the synthetic adhesives used in the adhesion tests

Cold-curing poly-ester resin: a quantity suitable for two tests is made up as follows: 5 g Bakelite poly-ester resin S.R.17497, 0·2 ml. Bakelite Catalyst Q.17447 and 0·1 g C.I.B.A. No. 9 Thixotropic Filler are mixed less than an hour before use, and 0·2 ml Bakelite Accelerator Q.17448 is added immediately before use.

Cold-curing epoxy-resin: Araldite 33/1000 A & B (a two-part resin-hardener mix not requiring accurate measurement of quantities).

Hot-curing epoxy-resin: Araldite No. 1 hot-cured at 180°C. for 1 hr.

Epoxy-resin hot cured under 50–100 lb/sq.in. pressure: Redux K6 and Powder hot cured at 145°C. for 30 min.

SPRING MEETING 1961

Some Recent Developments in Brazing

By G. R. Bell, B.SC., A.R.S.M., A.R.I.C., A.I.M., M.INST.W.

The development of brazing techniques over the past 30 years is briefly described, and it is shown that brazing is now able to assist designers and production engineers in many complex applications not suited to other methods of fabrication.

Examples are given of successful applications to materials with high alloy contents for which nickel-base brazing alloys are most suitable. Consideration is also given to the choice of fluxes and attention is drawn to the need for careful design appropriate to the technique and the maintenance of correct joint clearances.

ALTHOUGH brazing as a joining technique has been in use for thousands of years, and some of the oldest brazing alloys differ little from modern standard compositions, until recently most brazing was employed either for decorative purposes or for components where performance in service of the brazed joint did not demand anything but very low properties in the filler metal. Within the past 20 or 30 years, realization has grown of the potential value to engineers of brazing, and with this the theory and fundamentals of the brazing process and development of improved filler alloys have been the subject of an increasing amount of study. The volume of literature produced since the war is indeed large and certainly could not be discussed adequately in a short paper.

The attachment of cemented carbide tips to steel shanks for the production of cutting tools and rock drilling bits, where the generally accepted joining methods by welding or mechanical means could not be considered, is an early example of the problems which gave impetus to brazing and emphasized the need to develop extremely good properties in a brazed joint in the face of considerable practical difficulties. Although carbides are not readily wetted by a copper-base brazing alloy the more serious drawback arose from the very great difference in thermal contraction of the carbide and the steel base between the brazing temperature and room temperature. This could induce disastrous stresses in the joint with failure of the component in service. Sandwich brazing, with an intermediate layer of a suitable alloy, provided one means of accommodating the differential cooling stresses. The tremendous technological advances achieved since the war in aeronautics, rocketry, guided missiles, and in atomic energy demand alloys of better and better properties. These often have to be fabricated in complex form and may present difficult manufacturing problems (Figs. 1 and 2), providing a field in which brazing can often offer assistance to designers and production engineers. In examining the potential of brazing, engineers are not only using the technique to an ever increasing extent, but are making continuous demands on the manufacturers of brazing alloys to provide new and improved alloys to meet changing metallurgical and engineering requirements.

Fundamental study of alloy systems, laboratory determinations of the mechanical properties of joints, etc., are important essentials for the intelligent formulation of brazing alloys; but it must be borne in mind that the composition and properties of the filler metal may change appreciably during brazing because of interaction between it and the base metal. Other properties, such as joint clearance, heating rate, purity and nature of the brazing atmosphere can all affect greatly the properties of the brazed joint, so this paper will comment on some recent lines of investigation and general principles which may have emerged from these, rather than deal with particular alloys and specific properties appertaining thereto.

Nickel-base alloys have provided much interest, nickel having a reasonably high melting point. It alloys easily with many other elements, and exhibits excellent corrosion resistance and reasonable high-temperature properties. The nickel alloys are compatible with many of the highly alloyed steels, the nickel-base and chromium-base high-temperature alloys, stainless steel, and other corrosion resistant alloys now used for many of the more specialized engineering applications. Nickel–chromium–iron alloys were the first to be used for high-temperature service,[1] the chromium imparting good high-temperature strength and oxidation resistance to the nickel base. Boron and silicon can be added to reduce the melting point so that complex materials result. These exhibit wide melting ranges, a desirable property for the production of a fillet joint, but requiring strict control of brazing conditions, for the alloys may show liquation and possibly grain-boundary penetration. A fillet is an advantage in ensuring that there is no point of high stress concentration in the joint. It will act also as a seal against any slight imperfections which may be in the joint itself, and may at times ensure that the outer layer of the braze remains at the same composition as was used initially.

Interaction between the metal being joined and the filler alloy may arise through various mechanisms such as solution of base metal in the filler, diffusion of the filler into the base metal by intergranular penetration or intracrystalline bulk diffusion. Constituents of the

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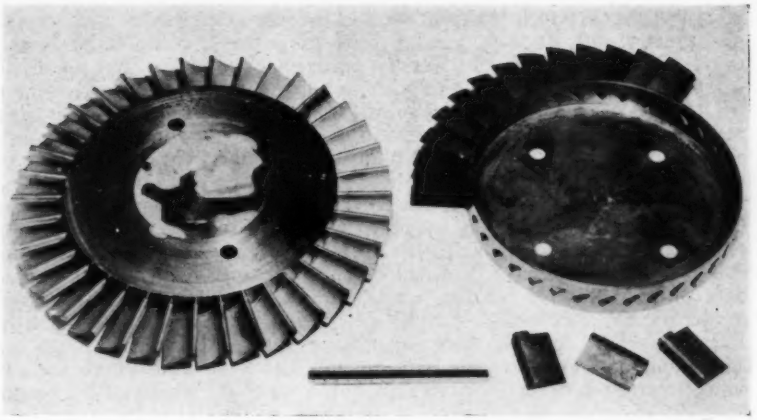
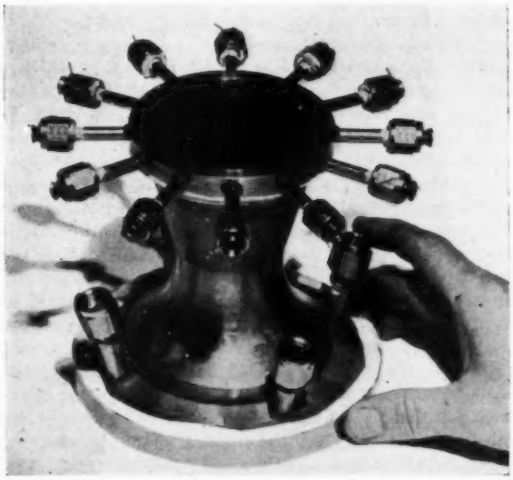


1—*Austenitic stainless steel (Type 347) turbine rotor produced from 38 separate pieces brazed with AMS 4775 type alloy (Standard Nicrobraz), in dry hydrogen, at 1175°C.*



2—*Nozzle assembly prepared for brazing. Components made in 18/8 stainless steel and pure nickel, using AMS 4775 alloy and Nicrocoat for surface protection. Note use of white stop-off material to limit flow of brazing alloy over surface*

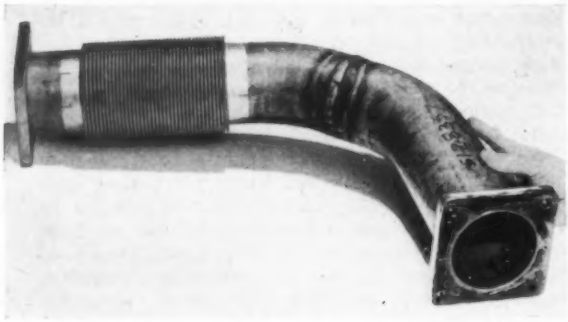
filler alloy may react with oxides on the base-metal surface to form slag products or a new alloy. Intermetallic compounds may form at the interface between filler and base metal. Additionally, composition changes may occur owing to the volatilization of an alloying element from the filler, and this in turn may be affected by the nature of the brazing atmosphere. Bredzs and Schwartzbart[2] have studied such base-metal/filler-metal interactions on steel brazed with copper and silver alloys. Their results suggest that saturation of the filler metal with base metal during brazing, followed by precipation of excess base metal within the filler-metal layer or on the base-metal/filler-metal interface, may be a universal phenomenon in brazing. Solution of iron in the copper and silver alloys was rapid, and at times saturation of filler metal occurred before the capillary gap was completely filled. The changing composition of the filler metal will alter the solidus and liquidus and, unless this is anticipated and allowed for, an inferior, incompletely brazed joint might result. In any case the mechanical properties of the filler metal could change appreciably. Preferential solution of the high spots on a rough metal surface will lead to a smoothing of the latter until the filler metal is saturated with the base metal. This could alter the apparent clearance of the joint and might necessitate initial specification of a good surface finish on the metal.

Canonico and Schwartzbart[3] studied the addition of indium and lithium to nickel–iron and chromium-base alloys to reduce the brazing temperature and assist the flow when brazing Inconel to stainless steel in a hydrogen atmosphere. The addition of lithium to nickel–chromium–germanium alloys provided material with oxidation resistance at 900°C.; but the use of indium resulted in loss of oxidation resistance. Indium is a very desirable addition to reduce the melting temperature and improve flow characteristics. Lehrer and Schwartzbart[4] examined the possibility of removing indium after brazing to restore the oxidation resistance alloy, which in turn would increase the melting point leading to an increase in the high-temperature strength and the development of a brazing system which could be used for successive build-up in a complex assembly using step brazing.

The two most important mechanisms which can give compositional change during brazing are solution of the base metal in the filler or selective diffusion of the filler, or constituents thereof, into the base metal to provide new alloys; or removal of an alloying element by volatilization to effect a change in composition. From theoretical considerations and experimental data it was concluded that the remelt temperature would increase only if the diffusing or the volatile element exhibited some solid solubility in the filler alloy. The effect on remelt temperature by either mechanism would be proportional to the solid solubility. The greatest increase in remelt temperature, in the absence of volatilization, was obtained with the nickel–indium–chromium–germanium quaternaries and a 6% P, nickel–phosphorus alloy. It is interesting to note that although phosphorus is very volatile by itself it is not removed from nickel alloys, even under vacuum brazing. A 39% In, nickel–indium alloy gave the greatest temperature increase owing to loss of an alloying element by volatilization. The nickel–chromium–indium–germanium quaternaries containing 26% In flowed and wetted the base metal well, and gave a

good increase in remelt temperature; but the increase was greater with vacuum brazing than in helium, suggesting that both diffusion into the base metal and volatilization could operate with such an alloy.

Diffusion of some of the filler metals into the base metal is an important consideration in many brazing applications, and is often used with advantage in the nickel–chromium–boron–silicon alloys of the type now covered by numerous AMS specifications.[5] Control of brazing conditions may give an increase in remelt temperature from about 1050° to 1350°C. or so. Peaslee and Boam[6] have provided much interesting data on the effect of brazing temperature on joint properties and mechanical strength of brazing with such alloys, as well as silver–manganese brazing alloys and brazes made with pure copper. There is some penetration of the base metal by boron which is both an advantage and at times a drawback of the alloys. It has been suggested that this action is associated with the wide solidus-liquidus range but



3—*Diesel engine exhaust tube assembly fabricated in austenitic, type 302, stainless steel. The bellows' wall thickness being only 0·010 in., is brazed to the two pipe sections using AMS 4777 (L.M. Nicrobraz) alloy in dry hydrogen at 1040°C.*

4—*Compressor turbine for aircraft air-conditioning system, brazed from 60 separate pieces in dry hydrogen using Standard AMS 4775 alloy*

Bredzs and Schwartzbart[1] found that eutectic alloys of Fe–B, Ni–B, and Pd–B will penetrate grain boundaries and dissolve base metals under varying conditions. Boron penetration has also been shown to be a function of the carbon content of either the base metal or the brazing alloy. Boron in most alloys, and silicon to a lesser extent, produces the effect of embrittlement as a result of the grain-boundary penetration. Cape[7] disagrees that boron diffuses selectively into stainless steel, and from microscope examination and hardness determinations concludes that other elements diffuse with boron into the base metal. This diffusion provides a mechanism whereby the ductility of the joint can be greatly increased by treatment at an elevated temperature. Although a disadvantage when fabricating honeycomb section from very thin sheet metal, the ability of the boron alloys to dissolve and diffuse into steel does permit the production of joints of considerably higher strength than can be obtained from the use of non-alloying brazing alloys, and the 7% Cr alloy (AMS specification 4777) is finding increasing industrial application (Fig. 3). It is used at a lower temperature than the widely applied AMS 4775 alloy (Fig. 4) and gives less rapid solution of the steel. By careful control of the brazing conditions satisfactory results have been obtained in the brazing of honeycomb sheets. The addition of 10% Co is claimed to reduce penetration of steel by the Ni–Cr–B alloy.[7]

Miller, Gonser and Peaslee[8] carried out brazing experiments, physical tests, and checks on oxidation and corrosion resistance on a number of binary and ternary alloys to provide fundamental information for the development of high-temperature brazing alloys. In line with many investigations T specimens were employed. These are fabricated by brazing together two strips of the required base metal. This type of test piece enables flow, wetting, and penetration properties to be examined easily; fillet formation can be assessed, whilst bending and twisting tests permit ready comparative examination of the mechanical properties of the joints. Conclusions drawn from these experiments were that although the flow and wetting properties of an 11% P, nickel–phosphorus alloy were excellent, ductility and oxidation resistance above 800°C were relatively poor. Surprisingly, high-phosphorus alloys containing more than 17% P showed superior properties. Ternary alloys were made by adding a third element to the low-melting 11% P alloy. The addition of silicon increased the oxidation resistance in proportion to the P/Si ratio. The extremely good brazing characteristics of these alloys suggest that the system offers good practical possibilities, but it seems desirable to add a fourth element to reduce the melting point of a high-silicon composition (it did not seem possible to produce a ternary eutectic), while retaining or improving the ductility, strength, and oxidation resistance of the alloy.

There are several eutectics in the Ni–Si binary system. One contains 12% Si another 29% Si. The lower alloy showed excellent brazing characteristics, physical properties, and oxidation resistance, but the melting point was higher than that of any of the phosphorus-bearing alloys. Ternary alloys were examined, based on both silicon contents even though the higher alloy had failed to provide a satisfactory joint because of the presence of SiO_2. Manganese

provided an interesting addition, the melting point decreasing until an alloy containing 7·5% Si, 22·5% Mn was reached. The manganese, besides lowering the melting point, increased the fluidity of the alloy without drastically impairing its oxidation resistance. The ductility was relatively good.

Many other alloy combinations were examined, particularly good results being obtained with Ni–P–Cr and Ni–Si–Cr alloys. Brazing metals based on both alloys have subsequently been developed commercially,[9] the former now having interesting possibilities in the atomic energy field, where resistance to high-temperature oxidation and attack from molten sodium may be required in an alloy free of boron, for the latter element is frequently not permissible in atomic energy applications.

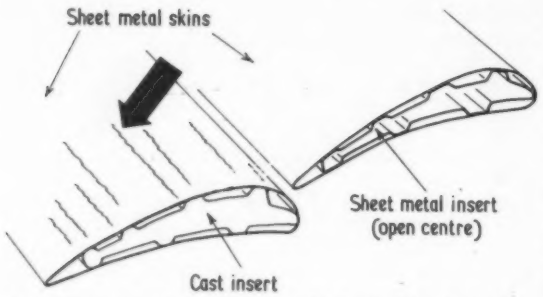
The 17–4 PH material is one that is difficult to join under almost any conditions. Cape[7] reports that the addition of 2% Ti to a Ni–B alloy permits the formation of sound joints, showing very good impact strength. Apart from metallurgical considerations, difficulties in normal production present problems to the manufacturers of brazing alloys. One is the difficulty of controlling gaps to extremely small tolerances. The gap must be sufficiently small to enable the brazing filler to flow by capillary action to completely fill the joint. However, too small a gap may inhibit complete penetration and with base metal reaction so increase the melting point of the filler that it solidifies in the joint. Various alloy systems are stated to be helpful in filling wide gaps. Two mentioned by Cape are 68% Mn–Ni alloys containing 1% Co, which is said to be useful in imperfect atmospheres, and a similar alloy containing 16% Co, advocated for joining stainless steels containing aluminium and titanium. Both are said to be able to fill gaps between 0·010 and 0·060 in. and to give excellent fillets. Another approach by the Wall Colmonoy Corporation has been the development of a special alloy, based on Ni–Cr–B–Si, which can be used on horizontal joints with clearances not exceeding 0·060 in. and on vertical joints with a 0·030 in. gap possibility. This Company manufactures also a 'Fillup' alloy powder which can be introduced into wide gaps to assist the flow of brazing material.[10] Palladium-containing alloys are considered in a paper by Hinde and Perry[11] who state that important properties, characteristic of these alloys, include the possibility of filling gaps up to 0·020 in. This property, combined with the ability to penetrate considerable distances, may provide considerable economy in manufacture, eliminating costly final machining operations to close dimensions. The ability to flow over a surface is associated with the wettability of the base metal by the brazing alloy. This wetting reaction between the two components has been the subject of considerable investigation by Feduska[12] for a number of high-temperature brazing alloys. Not only is the nature of the brazing alloy important, but the composition of the base metal can equally influence the wetting reaction. Of the base metals investigated, the Co-base alloys were most readily wet, whilst iron and nickel alloys containing titanium proved to be the most difficult. Nickel–chromium–silicon and nickel–boron–silicon alloys produced the best overall wetting. The performance of the former seems appreciably impaired either by an increase in the carbon content or by the presence of manganese. The only other alloys tested were Ni–Cr–Si–B–C and Ag–Mn. Considering the six alloys in general, vacuum brazing was superior to either dry hydrogen or dry helium in promoting wetting. Titanium will react with hydrogen, oxygen, or carbon to form a surface compound film which retards wettability. One interesting observation is that superheating generally produces a decrease in wettability. This was attributed to the increase in liquid-brazing-alloy/solid-base-metal interfacial tension at the higher temperature as well as to greater reaction between the filler and base metal. Cibula[13] has also investigated the spread of brazing alloy and emphasizes the need for rapid movement of the filler to the mouth of the joint so that capillary flow may begin.

The Pd-containing alloys discussed by Hinde cover twelve compositions developed for different applications. Of these, two based on Ag–Pd–Mn and one on Ni–Mn–Pd, were intended primarily for use in gas-turbine blading. The latter alloy overcomes a difficulty found if the Ag–Pd–Mn alloys are overheated, when segregation of a weak silver-rich solid solution occurs at the centre of the joint. Many modern brazing alloys are complex in structure, so producers must be alive to the danger that can arise from immiscible phases. The Ni–Mn–Pd alloy also offers good resistance to attack by sodium, and quaternary alloys which also include copper have been developed for nuclear energy requirements, for joining stainless steel without flux, in nitrogen. Such alloys exhibit very little base-metal attack.

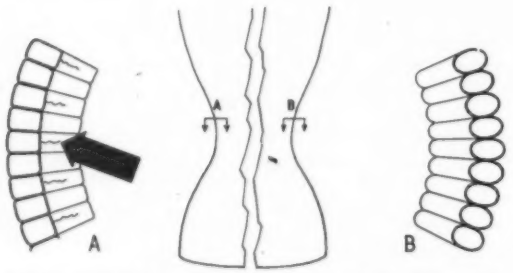
Among other metals and alloys for which special brazing materials have been devised are Inconel X, Cape suggesting the addition of sodium fluoride to AMS 4777 alloys, whereas Kinelski and Adamec[14] advocate a Pd–Ni alloy containing lithium and boron. It is claimed that graphite may be brazed to many types of stainless steel[7] using an alloy of 72% Au, 6% Cr, 22% Ni. Although this alloy dissolves steel, it does not penetrate rapidly. Lewis *et al.*[15] have investigated a number of titanium-base and silver-base alloys for brazing titanium, both to itself and to steels. Silver and silver–aluminum alloys gave successful titanium-to-titanium joints, but it is difficult to obtain ductility in a titanium-to-steel braze. The Ni–Ti eutectic has been covered by patents[16] for joining titanium and its alloys. Haskins and Evans[17] provide numerous references to articles dealing with the brazing of columbium, tantalum, beryllium, tungsten, and molybdenum, but space does not permit discussion of these.

Advances in aeronautical engineering have produced great interest in the manufacture of honeycomb panels, and numerous heating methods have been suggested for their production, uniformity of heat input and temperature control being very important. Fluxes which leave a solid residue cannot be entertained in such manufacture, and if fluxes are essential gaseous materials should be used. Ashley[18] considers the use of the boron trifluoride type of flux. Volatile fluxes are available commercially, as are brazing alloys containing volatile materials to improve cleansing of the base metal and to overcome deficiencies of marginal brazing atmospheres.[19]

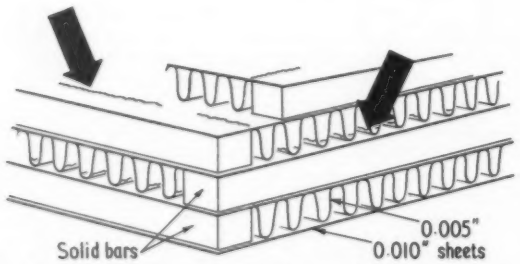
However good the brazing alloys, however carefully the metallurgical considerations are studied, the



5—Hollow, air-cooled turbine stator blades. Left hand side shows design using cast inserts and thin airfoil skin. The direction of thermal fatigue cracking is indicated. Right hand view shows a sheet metal design giving improved service life



6—Tubular rocket engine thrust-chamber brazements. The left sketch shows a 'square' tube design which when brazed presents a very rigid structure subject to thermal fatigue. The right sketch shows the tubular design which is more flexible and shows better service life



7—Corrugated sheet-metal heat-exchanger showing two points of failure found in this design. Both failures are caused by differential heating of the heavy bars and thin sheet metal

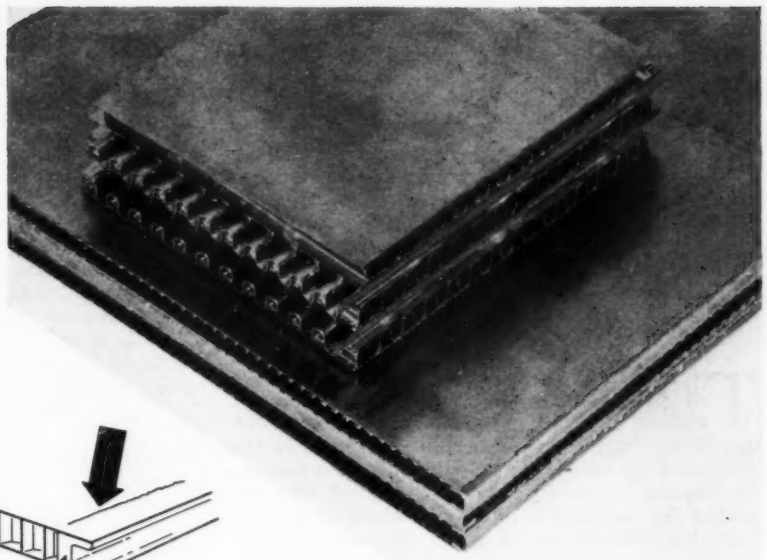
production of a sound brazed joint is impossible if initially it is incorrectly designed. The need for careful design, the realization for example that the joint clearance at the brazing temperature and not at the temperature of assembly is important, that difficulties may arise from differential thermal contractions between mating parts, and the possibility of distortion due to the heating cycle, have all been recognized by engineers for some time, and much more careful consideration is now given to the design of components. One danger which may not be generally recognized has been emphasized by Peaslee;[20] that is, the effect of thermal fatigue in causing the failure of brazed joints. There have been numerous cases in which the brazing has been blamed for failure of the joint but where analysis has shown that the assembly would have failed from fatigue anyway, had it been of welded construction or even made from one solid piece of metal.

Peaslee defines thermal fatigue as "the tendency for metals to break under conditions of repeated cyclic stressing considerably below the ultimate tensile strength, the stressing being produced by the non-uniform distribution of heat into the metal part." Thermal fatigue failure occurs at the grain boundary, with the failure starting at the point of maximum stress concentration where differential temperature is the greatest. The grain boundaries are oxidized and in severe cases metal oxide will appear to be exuding from cracks at the grain boundaries.

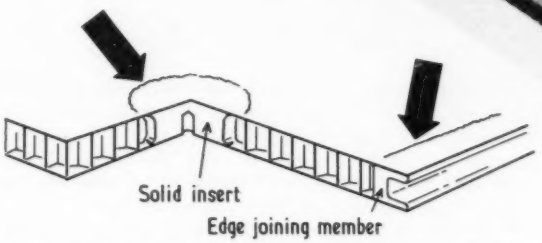
One of the major reasons for using brazing is in joining sheet metal to heavier sections, and thermal fatigue failure will occur at the point of change in cross-section. Case histories, taken from Peaslee's article, provide the best means of describing this type of failure and indicate ways in which it may be overcome. Figure 5 shows the approach of different companies to the manufacture of air-cooled turbine stator blades. In one (LHS) a precision-cast insert had a sheet-metal sheath brazed to it. In use, the heavy cast section heated very slowly, while the temperature of sheet metal rose rapidly; cooling occurred conversely when the engine stopped, and this led to the development of cracks in the positions indicated, because of the high stresses induced during the differential heating and cooling. The other method of manufacture shown involves the use of a thin sheet liner, which is both flexible and is heated much more uniformly at the nodes. Service life is greatly improved.

Figure 6 illustrates the production of a tubular rocket-engine thrust chamber. Sketch *A* shows the design based on 'square' tube sections. As produced initially, the tubes were brazed only at the outer diameter of the throat area, the tube angle being incorrect and excess clearance remaining along the sides between adjacent tubes. The assembly functioned satisfactorily, but acids produced on firing accumulated in the crevices on shut-down, and this condition was considered to be undesirable. Improvement in the production of the tube angles enabled the joint to be made completely along each interface between tubes, as is shown in the diagram, producing, in effect, two solid rings with stiffening struts between them. These thrust chambers failed, allegedly because the brazing alloy flowed across the surface of the tubes. Yet, on analysis, the failure can be shown to be due to the fact that the outside ring was approximately at room temperature while the internal section was overheated at the return tube, so that this metal upset, and when the engine was shut down the cold liquid rapidly quenched the overheated area, tearing the base metal apart. Redesign as shown at *B*, using 'oval' tube, has given comparatively little difficulty with thermal fatigue. The tubes are now quite flexible.

The manufacture of heat exchangers is becoming of greater importance both in aluminium-base alloys and in stainless steel. Figure 7 shows a corrugated sheet-metal heat-exchanger fabricated with heavy solid bars at the ends of the face sheets. After numerous cycles of operation between 535° and 850°C. leaks developed. Two different areas of thermal fatigue could be noted



8—*Successful design of brazed heat-exchanger plates. Note substitution of heavy, bar sections with* U *and* L *sections*



9—*Honeycomb structure subjected to high-temperature service. Thermal fatigue cracking is shown at the junction between the heavy and thin sections*

(indicated by the arrows), one where the 0·010 in. sheet runs parallel and adjacent to the heavy solid bar, the second where the 0·005 in. corrugated sheet is brazed over the heavy bar; in both locations heavy stresses will be produced during the heating and cooling periods. Figure 8 shows how such heat-exchangers may be made to avoid such difficulties. Similar troubles may be experienced with honeycomb sections, as is illustrated in Fig. 9. Cracking will occur if heavy inserts are used in conjunction with thin sheet metal. It is necessary to reduce the temperature gradient by using thinner, edge-joining members, and possibly to incorporate a tapered flange to broaden out the band of thermal-stress gradient. It is wise to avoid base metals which contain readily oxidizable constituents as these can permit concentration of stresses in the grain goundaries. At times, brazing alloys which have good high temperature oxidation resistance will reduce thermal fatigue development by covering the stressed area with a protective film, so preventing oxidation along the susceptible grain boundaries.

Brazing is playing an increasingly important part in production engineering these days, and whilst much thought has been put into the development of different alloys, many of which are now commercially available for different applications, further improvements may be expected in the next few years as the fundamental requirements for the production of sound brazes, particularly in new alloys, are worked out. The development of new and improved base-metal alloys, and the production of first class brazing alloys for use with them, must, however, be accompanied by improvement in design. The efforts of engineers must be to overcome deficiencies caused, not by the base metal, the filler alloy, or interaction between these two, but from factors in the design of the joint itself.

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Influence of Storage Time on Weld Metal Ductility

By Claes Pfeiffer

Tests were carried out on all-weld-metal specimens to determine how the storage time of the test bars influenced the ductility of the weld metal. The results showed that if the bars were stored long enough to avoid fish-eye formation the mechanical properties were approximately the same as those for degassed specimens. The tendency to fish-eye formation was influenced by the hydrogen content of the weld metal and also by the type of electrode.

THE hydrogen content of the weld metal as a cause of "fish-eye formation was first considered by Helin,[1] and the phenomenon has later been studied by many research metallurgists. Most of the research work has been done with tensile test bars as, for instance, work done by Hummitzsch[2] who has studied the contraction of all-weld-metal tensile test bars after different storage times. He found that the basic weld metals change their elastic characteristics only slightly due to fish-eye formation, and that no fracture surface had more than one fish-eye. As has been pointed out by Bastien[3] it is more correct to study the contraction of the test bar than the elongation, since the elongation is measured not only over the final fracture area but also over an extended length of the test bar and is thus less sensitive to the effect of fish-eyes. The contraction is measured over the fracture area. In this investigation both the elongation and the contraction have been studied.

Blake[4] has pointed out that the true rupture strength is diminished with rising hydrogen content but that the nominal rupture strength is not changed due to hydrogen in the weld metal.

Colbus[5] found that an annealing for 6 hr at 250°F. would cause the escape of the diffusible hydrogen from the weld metals which also, according to him, happens after three weeks' storage at room temperature.

This investigation was a study of the influence of storage time, up to 1,000 hr, on the reduction in area and the elongation of test bars made of all-weld-metal from five different types of electrode.

The electrode types tested are listed in Table I together with the ISO-designations and their mechanical properties. The all-weld-metal tests were made in accordance with the standards of the Welding Committee of the Swedish Academy of Engineering Sciences.[6] These state that the weld metal shall be welded on a base material of rimmed steel with the following chemical composition:

C max.	0·07%	P max.	0·05%
Si „	0·03%	S „	0·04%
Mn „	0·35%	Cu „	0·05%

The beads laid down with each electrode shall have a length of 200–250 mm, and the interpass temperature shall be 100°C. max.

Figure 1 shows the test bar and the U-shaped base material on which the weld metal was deposited. The test bar had a diameter of 10 mm and a gauge length of 50 mm. The test bars were stored in the machined condition at room temperature.

The chemical composition and the hydrogen content of the weld metal determined at 45°C., as well as the coating moisture are given in Table II.

The hydrogen test was performed so that four test specimens were prepared by depositing a single bead of weld metal on each of four plates measuring $\frac{1}{2} \times 1$ in. $\times$ approx. 5 in. long, using 5 mm dia. electrodes under the manufacturer's recommended welding conditions.

Before welding, the plates were thoroughly cleaned and weighed to the nearest 0·1 g. The weld beads were about $4\frac{1}{2}$ in. long, and within 30 sec of the completion of welding the specimens were quenched in water at 20°C.

Within 120 sec of the completion of welding they were cooled, cleaned, and placed in apparatus suitable for collecting hydrogen by the displacement of glycerine. The specimens were immersed for 48 hr in the glycerine, maintained at a temperature of 75°C. The specimens were again weighed to determine the weight of weld metal deposited.

The test conditions described have been criticised. Zeyen[7] has pointed out that the test has to be continued for two weeks in order to ascertain the total

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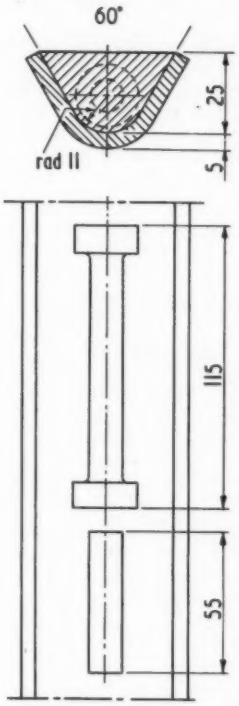
Table I — Mechanical properties of electrodes

ISO-Code	σ_T min *kp/sq.mm*	σ_T min *lb/sq.in.*	δ_5 min %	A_k min *ISA* *kpm/sq.cm*	*Usable Welding Position*	*Type of Current*
E432 R22	52	74,000	22	7	All positions except vertical down	a.c. (50 V) and d.c. straight polarity
E332 T22	48	69,000	22	7	All positions except vertical down	a.c. (50 V) and d.c. straight polarity
E423 C16	52	74,000	18	9	All positions	a.c. (70 V) and d.c. reverse polarity
E243 A24	44	63,000	26	9	All positions except vertical down	a.c. (70 V) and d.c. both polarities
E355 B29	48	69,000	30	13	All positions except vertical down	a.c. (95 V) and d.c. reverse polarity

Table II — Weld metal compositions and hydrogen contents

ISO-Code	*C, %*	*Si, %*	*Mn, %*	*Mo, %*	*Hydrogen, cc per 100 g Weld Metal (ASTM A233–48T)*	*Moisture Content, % (105)*	*(150)*	*(1,000)*
E432 R22	0·10	0·40	0·50	—	30	1·0	—	—
E332 T22	0·10	0·25	0·40	—	23	1·4	—	—
E423 C16	0·09	0·25	0·50	0·40	41	3·2	—	—
E243 A24	0·10	0·20	0·40	—	22	—	0·5	1·7
E355 B29	0·10	0·60	0·60	—	6	—	0·12	0·48



1—*Tensile test bar, 10 mm dia., 50 mm gauge length impact test bar, I.S.A.*

amount of diffusible hydrogen. Sadowski and Richter[8] have also referred to the influence of the viscosity of the glycerine, and Roux[9] has suggested the use of mercury instead of glycerine.

Test Results

The test results are shown in Figs. 2–11. The presence of fish-eyes is symbolized with a cross. The results from test bars tested after degassing for 16 hr at 250°C. are shown by open circles to the left in the diagrams.

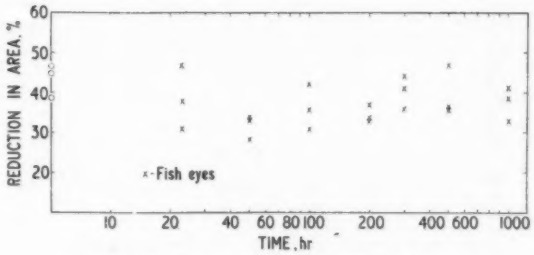
It seems to be easier to observe the influence of fish-eyes when studying the reduction in area than when studying the elongation but the tendency towards low values owing to fish-eye formations is obvious also in the diagrams that show the elongation as a function of storage time.

The rutile electrode E432 R22 has the next highest hydrogen content (Table II), and Figs. 2 and 7 show that both the reduction in area and the elongation are markedly influenced by the fish-eye formation. At the same time it is obvious that the tendency to fish-eye formation has not disappeared after 1,000 hr.

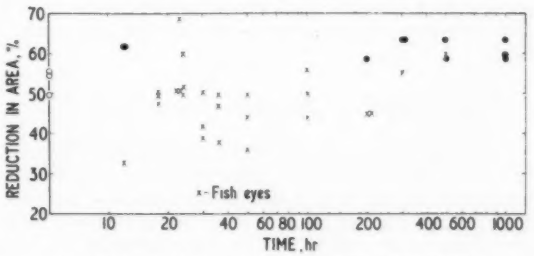
The TiO_2 electrode type (Figs. 3 and 8) shows fish-eye formation after a storage time of 18 hr; the critical time is between 0 and approx. 300 hr. After that time both the reduction in area and the elongation have reached values which are slightly better than those of test bars which have been degassed. After 300 hr the fish-eye formation seems to occur only occasionally.

It is of interest that values obtained from test bars which had been stored so long that no fish-eyes were formed are better than those for test bars which had been degassed. This same tendency is shown by other electrode types than EXXX T XX.

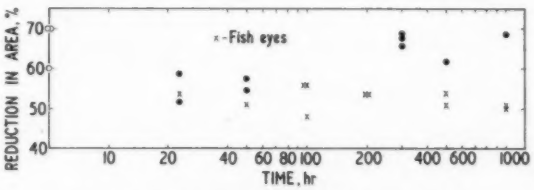
The cellulosic type of electrode (Figs. 4 and 9) tested shows only occasional fish-eyes up to storage times of 100 hr, and the tendency to fish-eye formation has not disappeared after 1,000 hr. At storage times less than 100 hr the fish-eye formation is very slight,



2—*Reduction in area—Electrode ISO—E432 R22*



3—*Reduction in area—Electrode ISO—E332 T22*

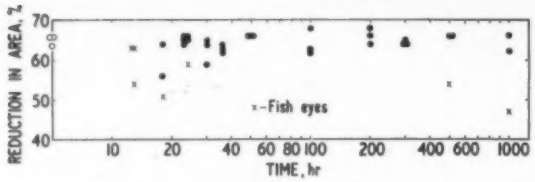


4—*Reduction in area—Electrode ISO—E423 C16*

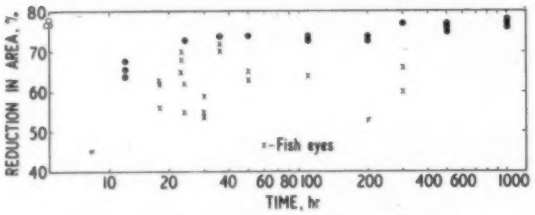
but the influence of hydrogen on both the reduction in area and the elongation is apparent without the formation of any visible fish-eyes. This same feature applies to the basic-coated type of electrode.

Test bars from acid electrodes (Figs. 5 and 10) show fish-eyes in only a few test bars after both short and long storage times. There seem to be slightly lower reductions in area and elongation during the first 50 hr after welding, but subsequently there seems to be no influence of hydrogen on the ductility of the weld metal if no fish-eyes are formed in the test bars. The results obtained from test bars which had not been degassed but stored are also for this type slightly better than those from degassed bars.

The basic-coated electrode type (Figs. 6 and 11) shows fish-eye formation after 18 hr but not after 12 hr and the tendency to fish-eye formation is limited to a short time, about 50 hr after welding; from that time fish-eyes are formed only occasionally. During the first period after welding the ductility of the test



5—*Reduction in area—Electrode ISO—E243 A24*

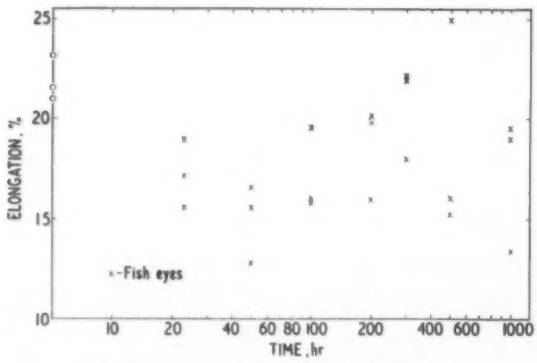


6—*Reduction in area—Electrode ISO—E355 B29*

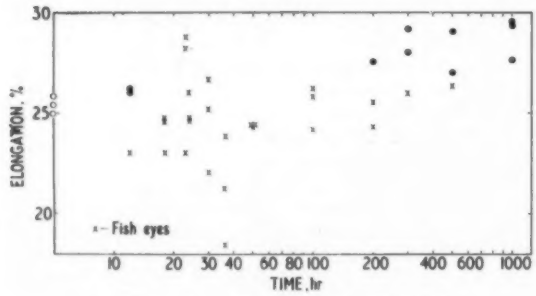
bars which had not been degassed is worse than that of degassed bars although there was no fish-eye formation.

Determination of Hydrogen Content at 650°C.

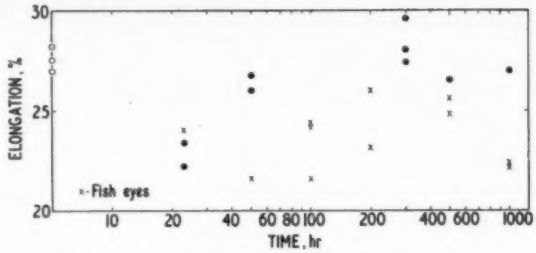
A few bars were tested with respect to the hydrogen content extracted at 650°C. The determination of the hydrogen content was made on the threaded portion of the test bar, since this part is unstressed. The specimens were placed in dry ice immediately after testing so as to retain the hydrogen in the weld metal until the analyses were carried out.



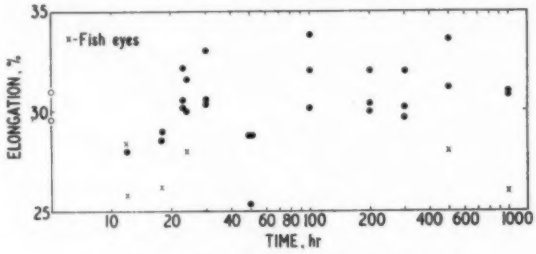
7—*Elongation—Electrode ISO—E432 R22*



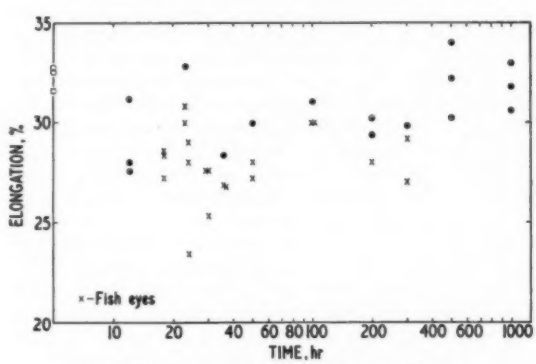
8—*Elongation—Electrode ISO—E332 T22*



9—*Elongation—Electrode ISO—E423 C16*



10—*Elongation—Electrode ISO—E243 A24*



11—*Elongation—Electrode ISO—E355 B29*

The hydrogen was extracted under vacuum in a modified apparatus described by Bjerkerud[10,11] and the gas was analysed in a microgas analysis apparatus according to Feichtinger.[12] The results of this hydrogen determination are given in Table III. The values show the hydrogen content of the test bars in cc per 100 g of weld metal at NTP. Fish-eyes were observed in the bars for which the hydrogen content is in bold figures.

Discussion

From Table III it is clear that the fish-eye formation is not due to the hydrogen content itself but to the type of weld metal. The basic-coated electrode type has produced fish-eyes at a hydrogen content of about 2 cc/100 g but the acid electrode type shows no fish-eyes in spite of its high hydrogen content.

There are also test bars with very high hydrogen contents which have not resulted in fish-eyes; for

Table III — Hydrogen, cc per 100 g (NTP) extracted at 650°C.

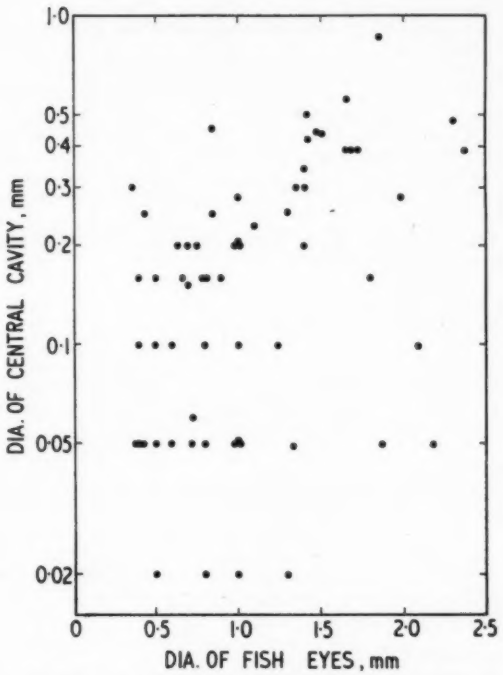
ISO-Code	Degassed at 250°C. for 16 hr	Storage Time 50 hr	100 hr	200 hr	300 hr	500 hr	1,000 hr
E432 R22	10·9	**9·5**	—	**5·6/7·3**	**6·6**	**7·3**	**8·2**
E332 T22	—	**22·5**	—	19·6/**27·2**	—	—	—
E423 C16	4·5	11·90	**13·78/12·48**	—	9·4/12·0	9·9/**13·4**	—
E243 A24	—	6·4/6·9	3·8	—	4·1	—	—
E355 B29	—	**1·97/2·64**	—	—	—	—	—

instance, the TiO_2 type after 200 hr and the cellulosic type after 500 hr, in each case one test bar out of three without fish-eyes.

The difference in slag distribution and cavities in the weld metal of other types as well as the difference in the supply of hydrogen from the coating components, and thus the different H_2–O_2 balance in the weld metal, is a possible explanation of the fact that fish-eye formation is due not only to the hydrogen content but also to the type of welding electrode.

The degassing means not only a diffusion of the hydrogen to the surface of the test bar but also a diffusion to inner cavities in the weld metal, for instance to slag inclusions and pores. The hydrogen determined at high temperatures may therefore, after degassing, reach values as high as those after a short storage without degassing. The hydrogen content of the weld metal is distributed in a different way after the degassing and no fish-eyes are formed because in the degassed test bar the hydrogen is to a certain extent in the molecular form, whereas in a test bar which is not "degassed" the hydrogen is so distributed that, during testing, it diffuses to places predestinated for fish-eye formation, such as macro- and micro-fissures and pores and other types of cavity. In cases when the test result is influenced without the formation of visible fish-eyes it is possible that part of the hydrogen is concentrated at dislocations of any kind.

In many test bars more than one fish-eye was formed during testing. This occurs with all weld metals. There seems to be no correlation between the area of fish-eyes and the area of the test bar before or after testing. The relationship between the diameter of the central cavity and the diameter of the fish-eye has been studied, but there seems to be no exact correlation between them. The results are shown in Fig. 12.



12—*Relationship between size of central cavities and fish-eyes*

Conclusions

(1) Storage of tensile test bars during a certain time is equivalent to degassing at 250°C. for 16 hr with respect to the tendency to fish-eye formation. The storage time necessary is dependent on the electrode type used.

(2) The storage time needed to prevent fish-eye formation is dependent on the electrode type.

(3) The ductility of the weld metal, after storage times long enough to avoid fish-eye formation approaches at least the same values as those obtained after degassing of the test bars.

(4) The tendency to fish-eye formation is not only due to the hydrogen content of the weld metal but also to the type of electrode used.

(5) There seems to be no exact correlation between the diameter of the central cavity and the diameter of the fish-eye.

Acknowledgment

The author thanks Elektriska Svetsningsaktiebolaget for permission to publish these results and is grateful to Messrs. K. A. Wallén and B. Söhrman for help with the hydrogen determinations as well as to Mr. Bini for the help with preparation of test bars.

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TENTATIVE RECOMMENDED TERMS AND DEFINITIONS FOR THE WELDING OF THERMOPLASTICS

THE Joint Committee on the Welding of Thermoplastic Materials, which is sponsored by the Plastics Institute, The British Plastics Federation, and the Institute of Welding, has been examining the existing terms and definitions for the welding of thermoplastic materials. The Committee is of the opinion that some improvement in the definitions is desirable, and that a number of further terms should be included. A study of this subject was, therefore, undertaken and a list of recommended terms and definitions has been prepared. This list has been approved by the three sponsoring organizations for issue as a tentative recommendation.

The Joint Committee will welcome comments on the following recommended terms and definitions; comments may be submitted to any of the three sponsoring organizations.

The references (in parentheses) indicate the British Standard in which the term is already defined.

Dielectric welding
See High-frequency welding.

Filler rod
A rod of thermoplastic material used in hot gas welding, to provide a source of softened or molten material to fill a welded joint. (BS.1755: 1951—No.7605.)

Flame sealing
A welding process in which the surfaces to be united are softened by the heat of a flame.

Friction welding
A pressure welding process in which the surfaces to be united are softened by heat generated by friction. (BS.1755: 1951—No.7611.)

Heat sealing
A term applied particularly in the packaging industry to the welding of thin thermoplastic materials (generally below 0·020 in.).

Heated tool welding
Radiant heat sealing. Radiant heat welding.
A pressure welding process in which the surfaces to be united are softened by conduction or radiation of heat from heated tools.

High-frequency welding
Dielectric welding.
A pressure welding process in which the surfaces to be united are softened by heat produced by a high-frequency field. (BS.1755: 1951—No.7602.)

Hot gas welding
A pressure welding process in which the surfaces to be united are softened by a jet of hot air or inert-gas produced by a welding torch. (BS.1755: 1951—No.7603.)

Impulse sealing
A pressure welding process in which the surfaces to be united are subjected to rapid heating followed by cooling, pressure being maintained over the whole of the cycle.

Induction welding
A welding process in which the surfaces to be united are softened or melted by heat transferred from an electrical conductor which is embedded in the thermoplastic and is itself heated by currents induced in it by an alternating magnetic field.

Molten bead sealing
A welding process in which the thermoplastic material at the joint is melted by the extrusion of molten beads on top of two overlapping sheets.

Pressure welding
Any welding process in which the weld is made by sustained pressure while the surfaces to be united are in a softened condition. (This definition is based on BS.499: 1952—No.2401.)

Radiant heat sealing
See Heated tool welding.

Radiant heat welding
See Heated tool welding.

Seam welding (including continuous and intermittent heating processes)
A pressure welding process which forms a continuous welded seam in which the surfaces to be united are softened either by heat produced by a high-frequency field or by conduction of heat from heated rollers or bars. The pressure may be applied continuously by rollers or progressively, as in stitch welding. (BS.2759:1956—No.427; BS.1755: 1951—No.7608.)

Spot welding
A pressure welding process in which a relatively small area of the surfaces to be united is softened either by heat produced by a high-frequency field or by conduction of heat from heated electrodes. (BS.2759: 1956—No.428; BS.1755: 1951—No.7610.)

Stitch welding
A pressure welding process in which the surfaces to be united are softened either by heat produced by a high-frequency field or by conduction of heat from heated tools. The pressure is applied progressively along the joint by two mechanically operated metal fixtures. (BS.1755: 1951—No.7607.)
(*Note:* This definition does not include high-frequency welding with patterned electrodes simulating stitch markings.)

Ultrasonic welding
A friction welding process in which the friction is intermolecular and is set up by ultrasonic vibration.

Welding torch
A device used in hot gas welding to heat air or an inert-gas and to direct it in the form of a jet on to the area to be welded. The gas may be heated electrically or by passing it through a tube heated by a gas flame. (BS.1755: 1951—No.7604.)

Note: The term 'sealing' is currently used and appears in the above terminology. In every case above it means "welding" and the Joint Committee recommends that consideration be given to the future elimination of this unsatisfactory term.

Welding RESEARCH

B.W.R.A. REPORT

Ultrasonic Welding

By S. W. Neville, B.SC.(ENG.)

Welding by ultrasonic vibrations without the use of external heat is a comparatively new technique. Preliminary investigations were carried out by B.W.R.A., first with a rig applying axial pressure between the centres of two rotating discs, secondly with a rig using a vibrating reed principle and thirdly with a modified ultrasonic cleaning set using piezo-electric barium titanate crystal blocks. The development of these rigs and the results of the tests carried out are described and although it is concluded that none of these methods could achieve the results obtainable by using the more conventional nickel magnetostrictive transducers, a considerable amount of knowledge has been consolidated and added to the general understanding of the subject. A chronological survey of the literature dealing with ultrasonic welding is included in the report.

History and Development—General Outline

In 1950 research workers in the U.S.A. found that the comparatively high surface resistance of aluminium and its alloys could be reduced sharply by applying bursts of ultrasonic energy through the electrodes of the welding machine.[1] The occurrence of welding in the absence of welding current in the secondary loop of the spot welder indicated the possibility of bonding by ultrasonic energy alone, and a programme of experiments was carried out with these possibilities in mind.[15]

Although this early work was mainly confined to soft aluminium foil,[15] it was soon realized that the process could be used successfully to join such materials as copper, nickel, titanium, zirconium, and some of their alloys, such as brass or stainless steel.[32,18] Attempts to weld combinations of dissimilar metals also resulted in bonds of surprisingly good quality and strength.

The subsequent development of transducers, couplings, and r.f. generators[42,21] revealed that in certain materials, ultrasonic welds possessed more desirable properties than those produced by resistance or 'cold' pressure methods, and in some cases achieved results hitherto unattained by the latter processes.

Although ultrasonic welding is generally regarded as having originated in the U.S.A., considerable research is being carried out in many other countries including the U.K., Germany[19] and Russia.[21,35] Much work has been done in Russia on the allied process of friction welding.[46]

Equipment

The equipment generally used for welding metals by ultrasonic vibrations comprises three important components, of which the first is the generator, a power oscillator fed from a normal 50 or 60 c/sec main and delivering a.c. at high frequency. The power from this unit is fed to the second component, which is a transducer for the conversion of the high-frequency (3–85 kc/sec) electrical energy[31] to mechanical vibration.

The final major component is the coupling, which directs the vibratory energy from the transducer to the workpiece.

As in most problems involving mechanical vibrations, frequency is a critical variable, as the amplitude

Report C41/3/60 of the British Welding Research Association, circulated to members in July 1960.

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of the forced component will be very much greater over certain narrow frequency bands than over the general range. The critical, or resonant frequencies are dependent upon the mechanical constants, such as mass, physical size, elasticity of the system, and, to a lesser extent, the damping. The importance of maintaining the welding system at a resonant frequency was soon realized, and modern r.f. generators are automatically tuned to the resonant condition.

Although there are many methods of generating high-frequency mechanical vibrations,[29] the magnetostrictive transducer appears to be specially suitable. This takes the form of a laminated nickel stack carrying two windings. The first winding carries d.c. for polarization, the a.c. power from the generator being fed to the second coil. The magnetostrictive properties of the nickel give rise to an alternating strain corresponding to the frequency of the input r.f. power.[43]

The relationship between resonant frequency and physical size, coupled with the magnetostrictive properties of nickel, make for a compact and efficient transducer, and this is the probable reason for its general adoption. The magnetostrictive transducer has a further advantage in that it can easily be coupled to the workpiece. The coupling generally consists of a solid cone, either bonded to, or as part of, the transducer core. The tip of this cone is arranged to bear upon the workpiece, either directly, or through a secondary component.[32] The material is supported by an anvil, which reflects some energy back into the workpiece.

Ultrasonic welding equipment of the type described is now available on the American market. It is claimed that a standard 4 kW machine will produce consistent welds in 0·071 in. Alclad sheet with tensile-shear strengths of over half a ton. A 100 W machine made by a different firm is reputed[20] to be able to produce seam welds in aluminium foil as thin as 0·0003 in. More powerful machines are in course of development,[31] with capacities of up to 8 kW.

Advantages of Ultrasonic Welding

The process has many inherent advantages:

1. No external heat is required
2. There is no evidence of general heating in the microstructures of the welds in soft materials[42]
3. Deformation may be less than 5% of the original double-sheet thickness
4. Power requirements from the main supply are low
5. Thorough cleaning is unnecessary[15]
6. Welds with good fatigue properties[38] may be obtained
7. Dissimilar metals can be joined successfully[42] and metals normally difficult to join, such as beryllium or molybdenum, can be dealt with[16]
8. Very thin foil, and combinations of sheets or foils of widely differing thicknesses may be welded satisfactorily.[6] This property enables components of awkward shape, such as fins to tube,[25] to be joined successfully
9. The process may be controlled to give consistent and reproducible results
10. If ultrasonic welding sets were manufactured in quantity they would possibly be much cheaper than resistance welding machines of equivalent welding capacity, as the large transformers and heavy construction of the latter would not be necessary
11. The ability to make continuous leak-tight seam welds in very thin foil makes ultrasonic welding an attractive proposition in the food packaging industry[20]
12. There appears to be no difficulty in making successive welds in close proximity to each other.

Metallurgical Aspects of Ultrasonic Welding and Mechanism of Bonding

Opinions vary considerably as to the exact cause of the bonding process.

Antenovich and Monroe[32] suggest that the surfaces under pressure, when made to slide relative to each other, become heated by friction. This local heating, together with the intimate contact brought about by the removal of oxide films and surface asperities creates a condition ideal for bonding, and a weld is eventually formed owing to recrystallization or fusion at the interface.

Byron Jones,[3] as early as 1955, compares ultrasonic welding with solid-phase cold-pressure welding and refers to work by Tylecote,[47] who established a relationship between the nature of the oxide films on metals, and the ease by which solid-phase bonding could be brought about by pressure alone. Byron Jones found that these relationships did not hold for ultrasonic welding, and he inferred that the surface condition of the material had only a slight bearing on the ultimate strength of the joint.

It would thus appear that ultrasonic energy breaks and disperses a contaminant such as the oxide film, allowing the clean metal surfaces to make intimate contact with each other. Anodized aluminium, or sheet metal thinly coated with paint, varnish, or the like, may apparently be dealt with successfully.[16,42] Once this barrier of contaminant is broken down, intimate contact would occur at the interface and, with the action of the externally applied pressure, a weld should form.

It has been established by Milner, L. R. Vaidyanath and others[48,49] that 'cold pressure' bonding is not possible unless the metal undergoes a noticeable degree of plastic deformation, as this internal disruption has the effect of breaking up the oxide layers on the faying surfaces. Virgin surfaces are thus brought into intimate contact under pressure and bonding takes place between them. Ultrasonic welding possibly relies on a similar mechanism, but as the plastic movements are created by the vibratory rubbing action instead of external force alone, the applied pressures and subsequent deformation required for welding are considerably less.

Effect of hardness and ductility

The analogy between cold-pressure welding and ultrasonic welding does not hold when the hardness and ductility of the metals being welded are examined. Little has been written on the cold-pressure welding of such materials as lead, tin, copper, or aluminium, all of which are comparatively soft and ductile. Harder materials have been pressure welded after preheating, the joint being made while the material is soft and inelastic. Ultrasonic welds, on the other hand, can be formed successfully in hard or refractory materials such as molybdenum, zirconium, titanium, stainless steels, or nickel, either in similar or dissimilar combinations. It is claimed that substances such as sintered aluminium powder have been ultrasonically welded.[16]

On the other hand, difficulty has been experienced in attempts to weld the very soft metals (lead, tin etc) by ultrasonic energy. This is almost certainly due to the high damping coefficients of such materials, most

of the energy being absorbed and dissipated before it reaches the interfacial zone. Work on very thin aluminium foil[10] indicates that if the thickness of the soft workpiece is so small as not to allow any appreciable losses due to damping, then a satisfactory ultrasonic weld may be obtained. The power required to obtain a weld thus appears to have a marked dependence on the thickness and hardness of the material. It is not difficult to understand the effect of thickness, as internal damping gives rise to greater losses as the thickness is increased.

A study of the effects of hardness of parent materials rather than their oxide films, would possibly throw some light on to the basic mechanism of ultrasonic welding. Consider two coupons of a soft material, such as fully annealed pure aluminium, cleaned and degreased. To effect a bond, ultrasonic energy is applied to an external surface of one of the coupons. This energy is expended partly in damping, partly in interfacial frictional heating, and partly in elastic and plastic deformation of the material. If the study were to be confined to thin coupons, the effects of damping loss would be minimized. This would leave three possible energy sinks—interfacial frictional heat, elastic deformation, which is recoverable apart from hysteresis, and plastic deformation.

A soft material, if thin, requires very little energy[9] (a clad material can be considered as a thin section, as only the cladding is soft, whereas the core material is generally hard and of comparatively low damping coefficient). The extremely short time required to make a weld in such a metal indicates, in this case, that a comparatively small amount of energy is used in frictional heating. The remainder would effect a local plastic deformation which, in the soft material, would rapidly disperse the brittle oxide and allow the solid-phase type of bond to occur.

If an attempt is made to weld a harder material, such as low carbon steel, it is found that, not only is a greater power required, but the time to produce a weld, and the normal pressure, must also be increased.[18]

Evidence of a temperature rise during the welding process has been studied by Byron Jones;[18] these temperatures appear to attain higher values in the harder materials.[45] The necessary heat is probably generated by direct friction of the unwelded faying surfaces. The temperature will rise until the material becomes soft enough to permit plastic flow. When this condition is reached the disruption at the interfacial zones will disperse the oxides and other contaminants, and a weld will subsequently form.

The time required to bring the interfacial zone to a plastic condition will of course depend on the frictional heating effect and on the normal pressure. By increasing this pressure and maintaining the ultrasonic vibration for as long as is required to attain the temperature at which the material will readily flow, a metal normally hard at room temperature may be welded. Hence a longer time and higher pressure are generally required for a hard material.

Present evidence suggests that although high temperatures are often encountered, these are invariably below the melting-point of the material, and thus no fusion occurs. The resultant weld is therefore a solid-state bond, whatever the hardness of the material. Recrystallization and grain-growth[38] are given by most workers as the reason for the strength of the bond, and most materials, notably nickel, molybdenum, copper, and aluminium exhibit considerable penetration of the zone of plastic disturbance into the parent material.[18, 11]

Ultrasonic vibration has the effect of grain-refinement, and is indeed used in foundry work for this purpose. Large grain structures are rarely encountered in ultrasonic welds, probably for this reason.

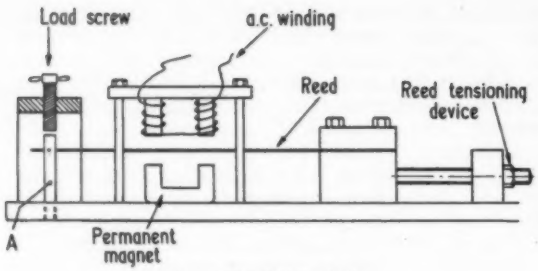
To sum up, it would appear that an ultrasonic weld is essentially a solid-phase bond. Materials which are brittle at room temperatures are heated by interfacial friction until they flow sufficiently to break the oxide layers. Soft materials flow under pressure at room temperature and do not require this frictional heat, although additional energy is required to overcome damping in thick sections. The high-frequency vibration has the effect of inhibiting the formation of large grains, and of removing particles of oxide and other foreign matter from the welded zone. The time taken to make welds should be short, otherwise fatigue cracks may occur in the newly formed weld. External deformation is very small and the fatigue strength of ultrasonic spot welds is claimed to be superior to that of welds formed by the resistance method, possibly through the absence of surface shrinkage.[38]

An interesting comparison of results may be obtained from references 45 and 46. In both cases a similar ferrous material was used, and the temperature rose steadily until welding was initiated, thus confirming the suggestions put forward in this report. The observations noted in the two papers differ after this point had been reached. Byron Jones, writing on ultrasonic welding, noted a rapid drop in temperature with time, while the Russian, V. I. Vill', concerned with friction welding, recorded a considerable rise. In both processes, however, it appears that a steady temperature is ultimately reached.

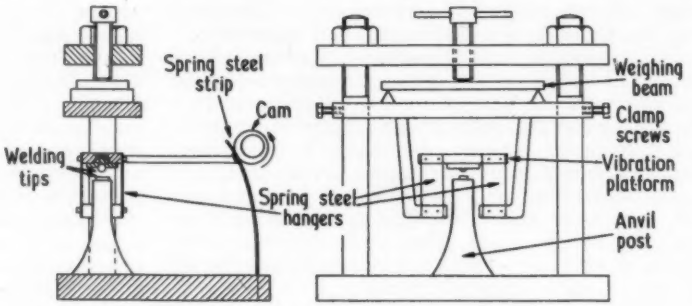
Work Undertaken by B.W.R.A. on Vibration Welding

Owing to the scarcity and high price of ultrasonic welding equipment at the time this programme of research was envisaged, it was decided that the use of a low-frequency rig would probably illuminate the basic mechanism of bonding and would, at the same time, be relatively cheap and simple to construct. Moreover, since mechanical power sources are in general cheaper than h.f. electrical sources, for a given power, the prospects of extrapolation to welds on thicker sections were thought to be better when using mechanical power. The possibility of obtaining sound welds at the low frequency was also considered to be attractive, and with these considerations, a programme of research on low-frequency vibration welding was undertaken.

Initially a rig applying axial pressure upon a small annular area between the centres of two rotating Alclad discs was used. These discs were subjected to an alternating bending stress produced by distortion caused by a stationary off-centre axial force, applied through a rolling contact. The alternating shear forces at the small central annular interfacial area thus created a relative vibratory movement between the two sheets which, together with the axial pressure,



1—*First redesigned rig*



2—*Second redesigned rig*

gave rise to a weld. The operating frequency was 47·5 c/sec. This work, started in 1957 by G. A. Phipps, has been reported in B.W.R.A. report No. ALR/111.

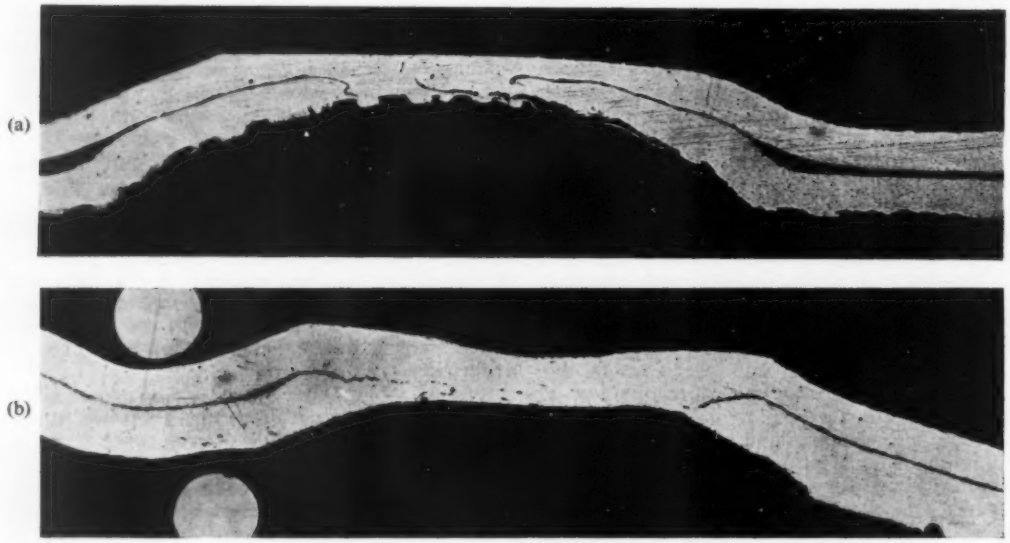
The rig, although proving that low-frequency welding was possible, possessed inherent disadvantages which prevented its use for further research. The shape of the test pieces necessitated considerable preparation and expenditure of material, and high-ductility materials, such as annealed aluminium or copper, were unsuited, as they would have become permanently dished by the rolling contact after the first revolution of the machine. It is also probably true that any weld formed in these materials would be due more to pressure alone than vibratory movement at the interfacial zone.

These shortcomings prompted the development of a completely new design of low-frequency welding rig, but first a general survey was undertaken of sources of mechanical vibrations, and their applicability to welding technique.[16]

The first redesigned rig, operating on the vibrating reed principle, as shown in Fig. 1, was not successful. This failure occurred mainly because the longitudinal elasticity of the reed reduced the effective amplitude at the tip, as the load P was increased. The anvil post A had to be of sufficient dimensions to resist distortion under the compressive load P, and the resultant damping decreased the amplitude even further. The machine operated at 50 c/sec.

It was decided at this point to use a mechanical principle for the second rig, and this is shown in Fig. 2. The results obtained from this machine were more promising, although welds of any sort were impossible in material more than 0·010 in. thick.

Welds did occur, though not consistently, between sheets of 0·010 in. commercially pure aluminium, but

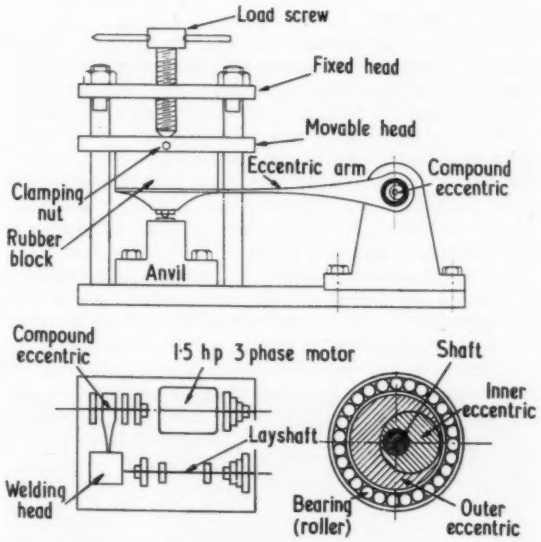


3—*Welds in two thicknesses of 0·010 in. 99·5% pure aluminium. Made on second design of low-frequency rig. 47·5 c/sec, 50 lb load, 5 sec welding time* ×25

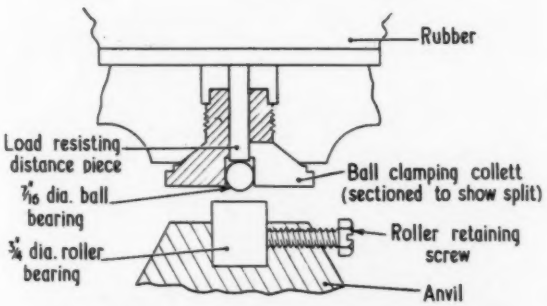
deformation of the sheet was high (50–70%) and weld strength was low. The optimum conditions for these results were amplitude ±0·005 in., pressure approx. 5,000 lb/sq.in., time 15–20 sec, and a frequency of 47·5 c/sec.

Welds made on this rig invariably pulled a slug from the parent sheet, and study of photomacrographs (Fig. 3) show the interfacial oxide layer as having been caused to run to the surface of one of the sheets. This would cause a slug to be pulled and would explain the very low strength obtained.

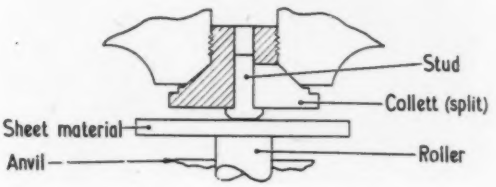
The rig eventually failed mechanically, and a further machine was constructed. The principle of operation was basically the same as before, but all working parts were considerably redesigned. Figure 4 gives a general idea of how variable amplitudes, frequencies and loads were obtained. The welding arrays are shown in Figs 5 and 6.



4—Detail of final low-frequency vibration welding rig



5—Welding array for sheet welding on 50 c/sec rig



6—Modified array for stud welding on 50 c/sec rig

Marked difficulties were subsequently experienced in maintaining consistent conditions with this machine. Owing to deformation the loading on the specimen changed while the machine was running. This change was difficult to monitor by conventional methods as the times were very short, and the whole rig was in a state of general vibration.

When frequencies were derived through the system of belts and pulleys it was found that high loads could not be used, owing to slipping of the belts. The full ranges of load and frequency were thus restricted, preventing observation of the behaviour of thick specimens of harder materials. Detection of frequency variation during running was readily audible.

Amplitudes remained reasonably steady, as the rigid construction of the rig prevented their variation to any noticeable extent. Doubt, however, existed as to the amount of 'lost motion' due to relative movements of the outer surfaces of sheet specimens with respect to the anvil or sonotrode of the machine. A stud-type welding array helped to overcome this problem (Fig. 6).

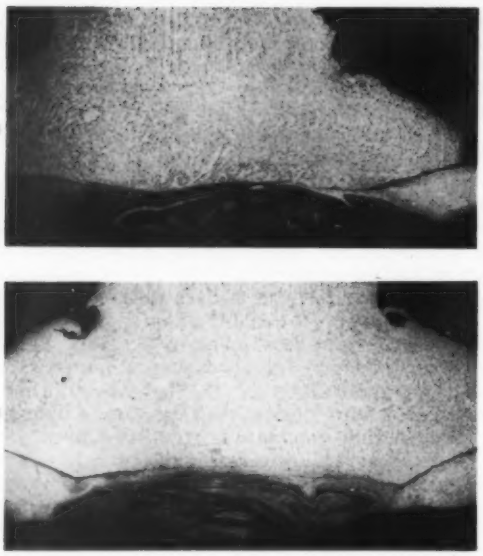
Results

In spite of these limitations, several important observations were made at a frequency of 50 c/sec. Clad alloys of aluminium in sheet form could be welded easily, with deformation of less than 15%. Soft materials, such as fully annealed copper or aluminium, could not be joined without excessive deformation. Thin sheets (0·010 in.) of soft aluminium, 99·5% pure, could be joined to 16 s.w.g. Alclad, and micrographs showed the turbulent disruption of the interface normally associated with ultrasonic (high-frequency) welding.

When the stud-type welding array was used, it was found that low-carbon-steel headed studs could be joined to 0·010 in. sheet of the same material. The parent material was considerably deformed, and the joints were weak and brittle. Higher frequencies (approx. 200 c/sec) were required with times of not less than 15 sec. Photomacrographs (Fig. 7) show that the sheet material deformed in the plastic state, with some cracking and oxide inclusion. The discoloration would indicate an effect of elevated temperatures in the sheet material, although there is no evidence of fusion.

One could deduce from these results that the bonding of metals resulting from low-frequency vibratory rubbing arises from the effects of plastic deformation, while under pressure. This will occur in the 'cold' state for soft materials, and at elevated temperatures, brought about by frictional heating, for harder metals.

The nature of the plastic flow in the welded zone, which can penetrate to an appreciable extent gives rise to the turbulent appearance of the section. This effect, which has been observed at frequencies much higher than 200 c/sec, appears to be a phenomenon peculiar to vibration welding. A study of welds in low-carbon steel made in short times revealed little evidence of cracking, but cracking becomes more severe if longer



7—*Welds between ¼ in. dia. mild steel stud and 0·010 in. mild steel sheet. Made on final low-frequency rig at 200 c/sec:* (a) *Weld made in 10 sec;* (b) *Weld made in 20 sec*

times are used (Fig. 7*b*). These cracks are possibly due to fatigue, or segregation of oxide and other contaminants brought about by plastic movements.

Comparisons with Ultrasonic Welding

General observations of ultrasonic welding by other investigators indicate that weld strengths increase with time up to a certain time. Longer weld times do not result in further increases in strength,[32] and sometimes a slight decrease is evident.[42]

The optimum time required to make an ultrasonic weld appears to be much less than that required for a low-frequency weld. Collins *et al*[42] give an optimum time of 0·8 sec to weld 0·020 in. Alclad alloy at 15,600 c/sec, whereas the 50 c/sec rig required several seconds. A much larger amplitude is required when using a low frequency, and it appears that this, coupled with the longer time, is an objectionable feature from the cracking aspect.

The use of an ultrasonic frequency means that a required amount of frictional heat can be generated in a shorter time than with a low frequency, although this effect is somewhat compensated by different working amplitudes. The criterion of sound bonding is, surely, to promote this shorter time and smaller amplitude, and thus to avoid the undesirable occurrence of surface deformation and fatigue cracking.

The main machine variable affecting frictional heat generation is the normal pressure. This factor also governs the process of internal plastic deformation and theoretically need be sufficient only to heat the interfacial zone to the state where it will deform to the required extent.

When a low frequency is used, a high force is required to ensure a rate of heat generation in excess of that lost to the sonotrode, anvil, and surrounding air or gas. This excess force has the undesirable effect of deforming the workpiece before the interfacial zone reaches its ideal state of plasticity.

Ultrasonic welding requires a much smaller normal applied force, as the high frequency causes more rapid heating, and the result is little or no external deformation.

It was decided to suspend work on low-frequency welding in favour of an investigation into the effects of higher frequencies made possible by the availability of new equipment.

Work on Ultrasonic Welding—General Approach

Choice of equipment

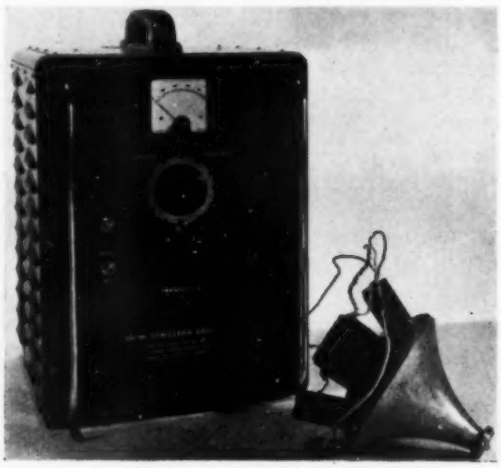
The references contained in this report show that all modern ultrasonic welding equipment makes use of the nickel magnetostrictive transducer. It was therefore considered that if B.W.R.A. research utilized similar equipment, then duplication of welding machine development work by others would occur, unless, of course, an up-to-date welding machine could be purchased. The financial resources available were insufficient to allow the purchase of the only commercial equipment available from America.

An ultrasonic cleaning set, marketed in this country, makes use of barium titanate transducers, and it was thought that if a method could be devised of coupling these transducers to a welding array, then welding equipment could be made commercially available by modification of devices at present in use for cleaning purposes. The programme of research into ultrasonic welding was therefore devoted to the development of an ultrasonic welding machine making use of available power sources and transducers.

Description of proprietary equipment

Generator

The power source used was a 500 watt 'Soniclean' type 1150 generator manufactured and loaned by Dawe Instruments Ltd. The unit contains a self-rectifying power oscillator of the Hartley type. Taps on



8—*500W generator and brass coupling horn*

the inductor permit coarse and fine setting of the oscillator frequency. A voltmeter, incorporated in the instrument, gives an indication of the energy output. The maximum electrical output at 40 kc/sec is about 125 W mean and 500 W peak. This ultrasonic energy is pulsed at 50 c/sec.

Transducers

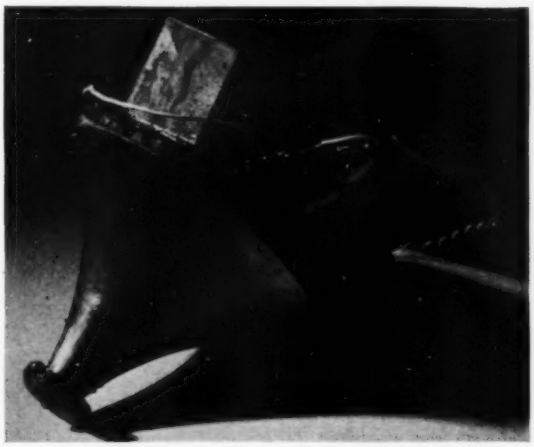
Barium titanate crystals are set into a closed cuboidal stainless steel housing so as to use one face of the housing as a radiating surface. These piezo-electric crystal blocks, normally used for cleaning, were also lent to B.W.R.A. by Dawe Instruments Ltd.

Photographs of both generator and transducer blocks are shown in Figs. 8 and 9.

Coupling

Ultrasonic cleaning devices invariably employ direct coupling into the cleaning liquid, and the large surface area of the pack of transducer blocks makes them ideal for this purpose. Welding, however, requires ultrasonic energy over a very small area, and the problem thus arises of focusing the energy from the large transducer surface to the welding sonotrode, which necessarily constitutes a small point.

The first step was to manufacture an exponential velocity transformer, as shown in Fig. 10. This 'coupling horn', turned from mild steel bar and polished on its curved surfaces, was $1\frac{1}{2}$ wavelengths long, with a diameter varying between 6 in. and $\frac{1}{4}$ in.



9—*Transducer blocks as fitted to brass horn*

10—*Steel horn (without transducer blocks)*

The object of the exponential shape was to reduce the effect of internal damping as far as possible by uniformly magnifying the amplitude of the vibration as the section of the horn became smaller, the amplitude being inversely proportional to the radius, assuming no damping.

Six transducer blocks were bonded to the larger end surface of the horn, this work being undertaken by Dawe Instruments Ltd. The tip of the horn was then progressively trimmed so as to tune the transducer–coupling assembly to the frequency given by the mid-tapping of the generator.

Experiments with steel coupling horn

Initial observations on the steel coupling horn indicated the energy available at the tip to be very low, and below the requirements for welding. This conclusion was reached by the following simple tests:

1. *Calorimetry of tip*

An aluminium calorimeter was externally lagged and mounted so that the tip of the coupling horn dipped into about 10 cu.cm of water contained therein. The horn was made to vibrate.

A temperature rise of about $\frac{3}{4}$°C. was noted after 5 min. This indicated that a very small amount of energy was reaching the tip, bearing in mind that heat conducted down from the more massive regions of the horn may have contributed to the measured rise in temperature.

2. *Microscopy of tip*

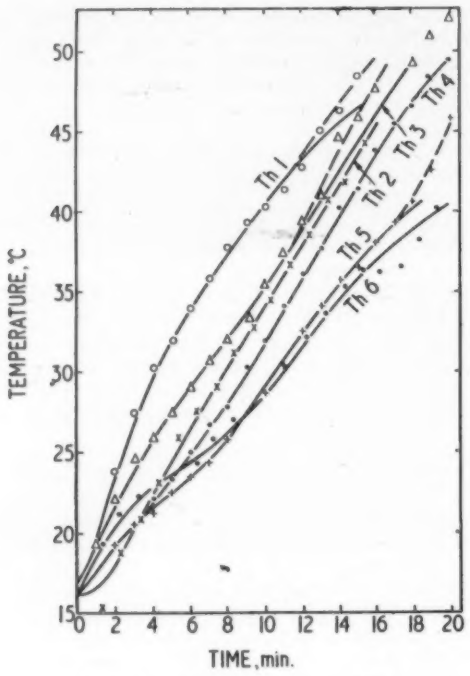
The vibrating tip was arranged so that microscopic examination was possible. It was found that very high magnifications were difficult to keep in focus owing to movement of the horn arising from thermal expansion and insufficient rigidity of mounting, but it was decided not to improve this as the results at $\times 250$ showed no oscillatory movement.

At the maximum magnification of $\times 250$ the rough edge of the tip appeared unchanged when the transducers were switched on and there was no evidence of vibratory movement. This indicated that the total was less than 100 microns, and probably even less than 50 microns, when running free. This amplitude would be reduced even further when a welding load was applied.

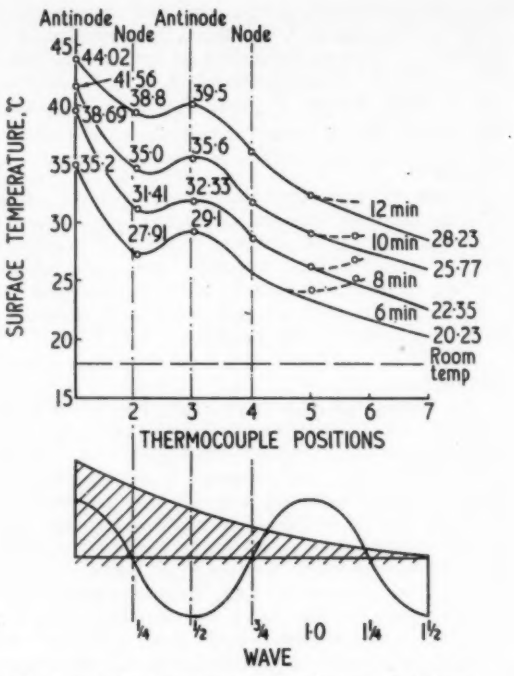
3. *Thermocouple measurements*

Although the foregoing tests indicated the coupling to be inefficient, a reason became apparent in the course of the investigation. It was noted that the steel became warm after transmitting for a few minutes, whereas the transducers themselves remained relatively cool. This effect could only have been caused by internal damping, and it was therefore decided to conduct a quantitative survey of heat generation in the horn, and hence try to assess the amount of energy available at the tip.

Thermocouples were placed in shallow depressions in an axial line on the curved surface of the horn at estimated $\frac{1}{4}$ wavelength intervals; in effect 1·5 in. spacings. Readings were taken by means of a potentiometer – galvanometer apparatus in circuit with a changeover switch, to enable the outputs of different thermocouples to be observed in succession without difficulty, and the equivalent temperatures were



11—*Temperature versus time. Steel horn*



12—*Longitudinal temperature distribution. Steel horn*

plotted to give a graph of temperature against time for each position (Fig. 11).

The results used to plot Fig. 12 were taken from readings observed in the 6–12 min interval.

Deductions

Losses due to internal frictional damping

To preserve the pattern of the investigation in general, the horn is considered to be divided into volumetric zones bounded by the nodal and antinodal positions. The temperature gradients are treated as linear between positions 1 and 2, 2 and 3, and 3 and 7.

Consider a small element dV of material of specific heat S and density ρ. Let the rise in temperature above ambient of this elemental disc be T°C.

Heat supplied to disc$=dQ=\rho dV \times S \times T$, but as the variation of T is assumed to be linear, this can be represented as $f(x)$ *i.e.*, $cx+d$. where c and d are constants relating to any particular zone.

$$\therefore dQ = \rho dV.S\{cx+d\}$$
$$\therefore dQ = S\rho\pi y^2 dx\{cx+d\}$$

The exponential curve to which the horn was designed is given by

$$y = ae^{-bx}$$

$$Q = -\left[\frac{\rho\pi a^2 S}{2b}\left\{e^{-2bx}\left(cx+\frac{c}{2b}+d\right)\right\}\frac{x_2}{x_1}\right] \quad \ldots\ldots\ldots \quad (1)$$

where $a=3{\cdot}125$, $b=0{\cdot}367$

From these relations it may be proved that for steel (< 1%C):

$\rho=128{\cdot}8$ g/cu.in. (assumed constant over temperature range encountered)

$S=0{\cdot}11$ g cal^{-1}°C.$^{-1}$

$a=3{\cdot}125$, $b=0{\cdot}367$

$$d=T_1,\ c=\frac{T_2-T_1}{x_2-x_1}$$

whence

$$Q=1{\cdot}65\left[e^{-2bx}\left\{\frac{(T_2-T_1)}{x_2-x_1}(x+1{\cdot}362)+T_1\right\}\right]\frac{x_1}{x_2}\text{cal/sec} \quad \ldots\ldots \quad (2)$$

Equation (2) can thus be used to calculate the heat supplied in the period from 6 min to 12 min after switching on. The results obtained were:

Zone A—	3,822 calories
Zone B—	1,328 ,,
Zone C—	570 ,,
Total	5,720 calories for 6 min period

Heat input from generator

The manufacturers of the equipment stated that the 500 W unit delivered 125 W average power when indicating full scale deflection. A 20% reduction in meter reading, which is the mean attenuation encountered, would indicate an average power of approx. 80 W.

Now 80 W$=80/4{\cdot}2$ cal/sec, giving a heat input of $80/4{\cdot}2\times 360=6{,}850$ cal over a period of 6 min. The resulting heat balance is therefore:

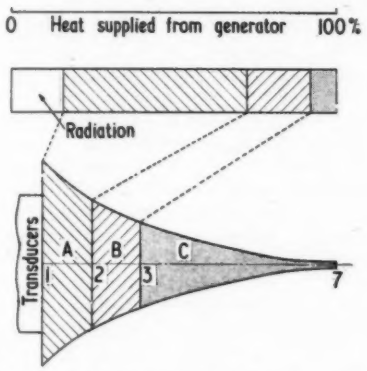
Zone A—	55·9%
Zone B—	19·5%
Zone C—	8·33%
Radiation etc.—	16·27%

The heat unaccounted for in the balance has been attributed to radiation and convection.

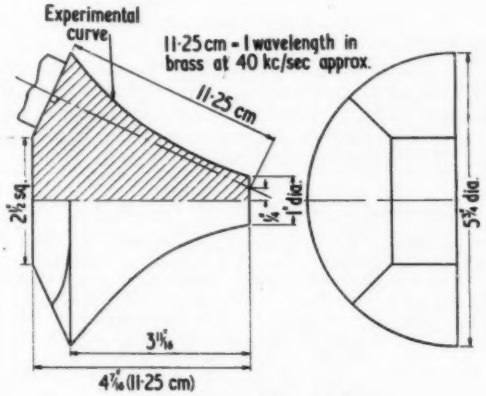
Radiation is a function of temperature, surface area and nature of the surface, and as the transducers themselves present the best conditions in all these respects, it is likely that most of the energy lost as radiated heat is never transferred to the coupling. It would also be fair to suppose that the small proportion that is transferred is dissipated by convection from the walls of the coupling in the area adjacent to the transducers, but the amount of energy lost in this manner in the region of the tip is negligible.

Conclusions

The results of this investigation indicate that the steel coupling horn is not suitable for ultrasonic welding purposes, as the losses created by internal damping are excessive. Even though all readings were taken when the coupling was running free, and most probably at a frequency slightly different from that occurring under load it will be noticed that the heat losses at the tip are very small. When the tip is not loaded, all the available mechanical energy in that region is reflected back into the material, and subsequently damped out into frictional heat. Figure 13 indicates that the amount of heat contained in the whole of zone *C* after running for a 6 min period only represented 8·33% of the energy supplied to the transducers. The available energy at the tip itself would almost certainly be no more than a quarter of this amount—perhaps 2 W maximum, and this can be considered as insufficient to weld anything but very thin foil.



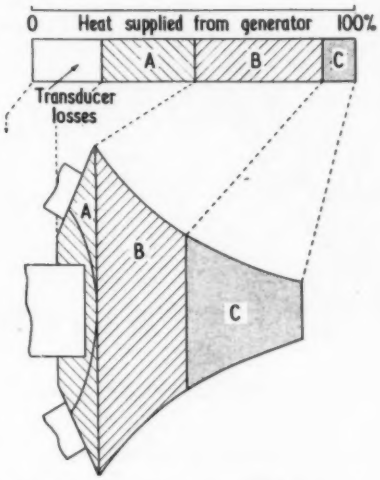
13—*Loss diagram showing distribution of input energy for steel coupling horn running free*



14—*Experimental brass coupling horn*

Brass coupling horn

The fore-mentioned shortcomings of steel as a coupling material led to the design of a modified unit. This was machined from 70/30 brass (Figs. 9 and 14), and was different from the former design in that the radiating surfaces of the transducers were directed towards the tip and the overall length was one wavelength, instead of 1·5 wavelengths, as in the former case.



15—*Heat balance diagram for brass coupling horn. 20 min period*

Subsequent experiments on the modified unit showed a slight improvement in performance, and although it was occasionally possible to weld 0·003 in. aluminium foil, the net output at the tip of the horn was generally insufficient for welding purposes.

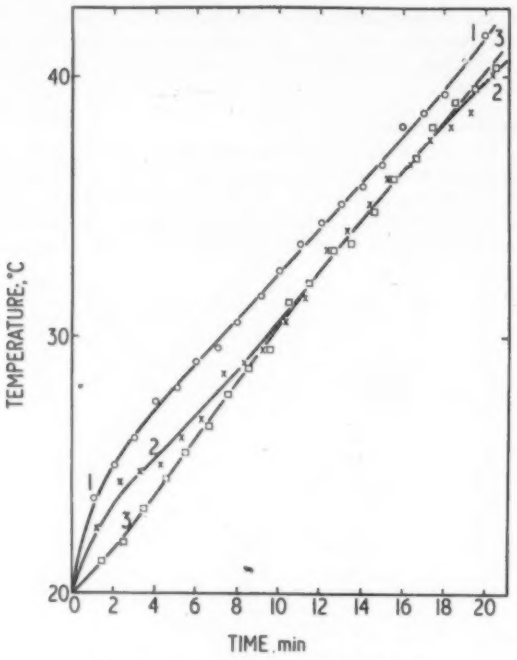
Thermocouples were attached to assumed nodal and anti-nodal positions and their readings over a 20 min period gave information for a heat balance to be drawn up (Fig. 15) by use of the curves in Figs. 16 and 17.

Deductions

The results of the temperature measurements indicated that a smaller percentage of input energy was reaching the tip than for the steel horn. The fact that steel has a higher damping coefficient than brass would tend to disprove the idea that the increased loss was due to internal damping. A better explanation, based on the fact that tuning for maximum input power was very difficult, would be that the natural frequency of the horn was not matched to that of the transducers. The angular orientation of the transducers may possibly have had a further adverse effect.

Calculations over 20 min period

$$Q_{A-B} = 292{\cdot}9\left[\frac{1{\cdot}6}{1{\cdot}61}(0{\cdot}92)+25{\cdot}4\right] - \frac{292{\cdot}9}{5{\cdot}755}\left[\frac{1{\cdot}6}{1{\cdot}61}(2{\cdot}53)+23{\cdot}8\right].$$



16—*Temperature versus time. Brass horn*

Net heat input zone $A = 6{,}364$ cal.

$$Q_{B-C} = \frac{292{\cdot}9}{5{\cdot}755}\left[\frac{0{\cdot}2}{1{\cdot}97}(2{\cdot}53)+23{\cdot}8\right] - \frac{292{\cdot}9}{48{\cdot}911}\left[\frac{0{\cdot}2}{1{\cdot}97}(4{\cdot}5)-24\right].$$

Net heat input to zone $B = 1{,}077{\cdot}6$ cal.

Overall heat input from transducers

Mean meter reading = 60

∴ Mean generator output = approx. 50W, and power to transducers over 20 min

$$= \frac{50 \times 20 \times 60}{4{\cdot}12} = 14{,}563 \text{ cal.}$$

This results in a heat balance:

To zone A = 43·7% of input;

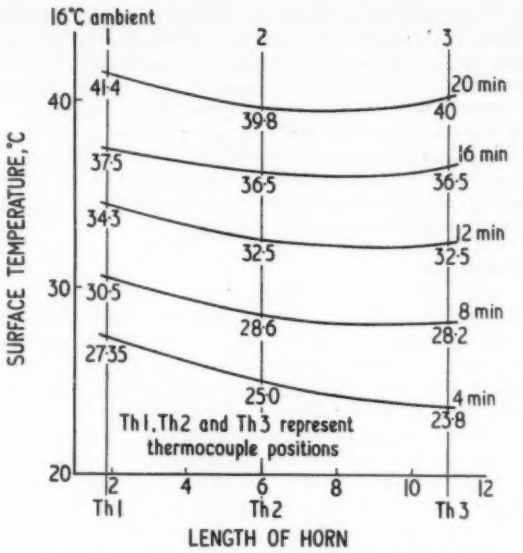
to zone B = 7·4% of input

∴ Heat unaccounted for = 48·9% of input.

General Conclusions

The work done on steel and brass coupling horns indicates that both designs had transmission efficiencies of the order of 8%. Although little has been written on the efficiency of magnetostrictive welding arrays, a study of weld sizes and input powers of such devices would suggest that these also work at a low coupling efficiency. They have the advantage, however, of being able to accept high values of input power that would invariably ruin a barium titanate transducer array.

The transducer elements used in the B.W.R.A. experiments were all working at their maximum input condition, and thus the problem would not have been solved by using a larger generator. This would have necessitated the use of more elements, and consequently a larger horn. The large mass of metal would probably give rise to increased damping losses and thus lower the efficiency even more. It is clear then that piezo-electric transducers, such as barium titanate crystals, are not at present suitable for welding purposes.



17—*Longitudinal temperature distribution. Brass horn*

The experiments with the low-frequency rigs did not give results of practical significance, although they threw considerable light on the mechanism of the process of vibration welding. Macrosections of welds made at the low frequencies revealed similar characteristics to those of ultrasonic welds, although the times and pressures required to make them were appreciably greater.

The need for increased weld time and pressure demanded greater frictional heat generation in low-frequency work to overcome losses to external sinks. This leads to excessive deformation (Fig. 3).

The use of higher frequencies overcomes the trouble, as the rate of interfacial heat generation is rapid, and the energy is thus confined to the zone where it is required, there being insufficient time for its dissipation.

The general conclusion of the research into vibration welding is that, although little practical advance has been made, a considerable amount of knowledge has been consolidated and analysed which, it is hoped, will add to the general understanding of the subject.

CHRONOLOGICAL SURVEY OF LITERATURE

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BOOK REVIEW

C. G. BAINBRIDGE: "*Practical Welding Repairs*", London, 1960, Temple Press, 128 pp. (15*s*.)

The author has broadened his field in dealing with welding repairs, since he jointly wrote a book with Frank Clark entitled "*Oxy-Acetylene Welding (Repairs) Manual*", by use of both gas and arc processes. In less than another 5 years time it will be more topical to extend, to a greater degree than now, the use of inert gas processes, for this already requires more than a casual reference, bearing in mind the advantages of the greater root penetration and the fact that many businesses, including small firms, now have the equipment. That is by no means a criticism of the general terms with which Mr. Bainbridge has produced remedies, and equally important are the hints he offers on the assessment of the metals and other details before preparation of the joint is ultimately decided. In other words, a hurried repair will soon land everyone on the debit side of the welding pool. The measured steps taken by the author will lead the reader through properties of metals, along the paths whether they be wrought or cast, until hard facing parts are reached, and on to miscellaneous repairs, finally reaching welding fields by the care of welding equipment; and the safety of his health is not neglected. Whatever else Mr. Bainbridge achieves in his book, he cannot fail to hold the practical welder who sets out to make a study of maintenace repairs, for he impresses on his subject the importance of this work; a warning, therefore, to those who could be guilty of too much self-assurance before they have even tackled their first repair.

This book should be of interest to works engineers as well as design personnel; it should be adopted for educational purposes in the technical advancement of welding, as related to repairs. Given faith in maintenace welding, it is an investment whether it be for use in a factory engaged in the production of toothpaste, or a large engineering works with a preponderance of bad teeth.

COLIN SPENCER

NEWS and Announcements

News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE ACTIVITIES

MEETINGS

SPRING MEETING 1961

Recent Developments in Welding and Allied Processes

The Annual Spring Meeting of the Institute will be held at 54 Princes Gate, London, S.W.7, from **25th to 28th, April 1961.**

The proceedings will include the delivery of the Fourth Annual Lecture by Dr. N. P. Inglis, a visit to the welded Maidenhead Bridge, discussion of technical papers, and the Joint Dinner with the London Branches.

The meeting has again been arranged to coincide with the Engineering, Marine, Welding and Nuclear Energy Exhibition. The official visit of members of the Institute, and the luncheon to members of Council will take place on the last day of the meeting.

The programme of the meeting is as follows:

Tuesday, 25th April

6.30 for 7.0 p.m.—Fourth Annual Lecture "*Welding in the Non-Ferrous Metals Field*" by Dr. N. P. Inglis

8.0–9.0 p.m.—Reception

Wednesday, 26th April

9.30 a.m.–12.30 p.m.—First Technical Session for the discussion of the papers:

"*Mild Steel Electrodes for Contact Welding*" by J. W. Addie

"*Mild Steel Welding with Argon/CO_2 Mixtures*" by J. A. Lucey, N. Crevis, F. W. Lunau, and B. H. Baker

"*Automatic Tungsten-Arc Welding of Heat Exchangers*" by N. T. Burgess

"*Inert-Gas Shielded Metal-Arc Welding of Thick Copper without Preheat*" by K. J. Clews

2.0–7.0 p.m.—Visit to the welded Maidenhead Bridge

Thursday, 27th April

9.30 a.m.–12.30 p.m.—Second Technical Session for the discussion of the papers:

"*Developments in Stud Welding* "by D. J. N. Laurie

"*Foil Seam Welding*" by F. Busse

"*Some Recent Developments in Brazing*" by G. R. Bell

7.0 for 7.30 p.m.—London Branches Joint Dinner at Quaglino's Restaurant

Friday, 28th April

9.30 a.m.–12.30 p.m.—Third Technical Session for the discussion of the papers:

"*Auto-Pneumatic Metal Spraying Machines*" by W. E. Stanton

"*A Note on Flame Spraying Developments*" by Ll. Manuel

"*An Adhesion Test for Aluminium Spray Coatings and other Metallized Surfaces*" by R. S. Smith and N. Stephenson

All day—Official visit to Engineering, Marine, Welding and Nuclear Energy Exhibition at Olympia.

Enrolment forms have been distributed to members. The last day for enrolment and application for tickets (reception, visit, dinner) is 17th April.

The papers for discussion are published in this (April) issue of *B.W.J.* with the exception of that by K. J. Clews. Preprints of this paper are being distributed.

Aluminium

Members of the Institute who would be interested to join the party which is going to Utrecht for the Joint Meeting with the Netherlands Welding Institute from 31st May to 2nd June, 1961, are urged to apply at once to the Institute for copies of the programme and enrolment form. The closing date for enrolment is **15th April.**

Sir William Larke Medal

On the recommendation of the examiners the Council has awarded the Sir William J. Larke Medal for 1960 to L. R. Vaidyanath and D. R. Milner, M.Sc., for their paper "*Significance of Surface Preparation in Cold Pressure Welding*".

The following paper received special commendation: "*Quelque remarques à propos de la qualité d'image radiographique*" by G. d'Herbemont, Ing., E.S.S.A.

The medal paper was published in the January 1960 issue of the *British Welding Journal*. The commended paper, presented at the Institute's Autumn Meeting 1959, was summarized in the October 1959, issue.

ELECTION OF MEMBERS

The following elections were made at the Council meeting of 15th December, 1960.

Members

†E. J. French (Cambridge); G. M. Harvey (London); B. Langshaw (Leicester); J. D. D. Morgan (Warrington); A. R. E. Singer (Swansea); *J. Strevens (Kent); T. R. Tighe (Redcar); *R. B. Whalley (Surrey).

Associate Members

R. L. Apps (Middlesex); S. Bandopadhyay (India); G. Buckton (Harrogate) C. A. Burden (Newcastle on Tyne);

S. R. Buttriss (Sale); J. E. M. Carlson (Newport); G. B. Clarke (Surrey); G. Cleworth (Bolton); D. F. Derbyshire (Manchester); A. F. J. Dix (Birstall); ||A. H. Garvey (Middlesex); A. B. Gibson (Swansea); ‡A. F. Gifford (Derby); J. F. A. Godley (Sheffield); L. G. M. A. Van Groos (Altrincham); D. A. Hollingsbee (Surrey); ‡J. E. Hooper (Bristol); B. Horsfield (Cheshire); ||J. R. Lewis (Middlesex); M. P. Malik (London); D. J. F. Moore (Essex); P. J. Palmer (Moseley, Birm.); R. S. Park (Surrey); A. H. Porter (Dublin); H. V. Roman (Macclesfield); N. Smith (Derby); P. Challis (Somerset), A. R. White (Dorset); G. Wyatt (Coventry).

Companions

L. W. Beer (Surrey); J. Braddock (Lancaster); W. Dowbiggin (Cumberland); A. Demacker (Glasgow); L. Ellis (Birmingham); T. G. Gibson (Glasgow); C. S. Low (Singapore); B. W. Ricks (Leicester); B. Stevens (Bucks); J. G. B. Stiles (Surrey).

Graduates

I. N. Banerjee (Lancs,); D. W. Bell (Wolverhampton); K. P. Bentley (Cambridge); R. C. Booth (St. Helens); M. C. B. Davies (Rutland); L. D. Ingham (Derbys.); R. Kapur (India); J. K. Pickett (Cardiff); P. E. Preston (London); M. J. Watts (Sussex).

Associates

C. W. Baker (Surrey); A. E. Biddulph (Birmingham); D. R. Birt (Birmingham) D. L. Butcher (Bath); G. W. Carnell (Solihull); P. H. Cassidy (Newcastle on Tyne); K. M. Chipperfield (Portsmouth); M. C. Dando (Rhondda); J. C. Eariss (Middlesex); R. B. Ebrey (Surrey); K. Eggington (Rotherham); J. L. Ensor (Castle Bromwich); D. E. Grainger (Kent); A. Harrison (Chester-le-Street); T. R. Horton (Swansea); H. P. Jaiswal (India); G. L. James (Wallasey); J. Joyce (Dorset); W. Kaye (Lancs.); W. Kenyon (Derby); H. Leeming (Stretford); J. B. Little (Leicester); S. McCabe (Sussex); F. W. D. Mailer (Glam.); D. S. Marjara (India); J. T. Merrick (Walsall); P. Mountain (Wakefield); A. Newton (Rotherham); W. Northorpe (Sunderland); D. S. Payne (Derby); D. R. Pearson (Wolverhampton); A. Powell (West Bromwich); G. Price (Sheffield); K. R. P. Sarathy (India); M. Sarkar (India); E. B. Smith (Slough); R. Smith (Durham); D. H. Sutton (Essex); J. E. Thomas (Basingstoke); A. E. Treeton (London); H. R. Vokes (W. Bromwich); T. P. Wallace (Caerphilly); G. D. Watkins (Cardiff); J. W. Watson (London); P. T. White (Middlesex); J. Williams (Swansea); P. C. Wilson (St. Neots).

Industrial Corporate Members

Haddon Transformers Ltd. (Middlesex); Hardy Spicer Ltd. (Birmingham).

Elected 15th September, 1960.

Associate Member

R. L. Moir (Surrey).

* Transfer from Associate Member.
† Transfer from Companion.
‡ Transfer from Graduate.
|| Transfer from Associate.

PUBLICATIONS

Radiographic Handbook

The Institute will shortly publish on behalf of the International Institute of Welding the English edition of the "*Handbook on Radiographic Apparatus and Techniques*". This book represents the views of the leading experts on this subject and deals briefly and simply with the apparatus and techniques for the radiographic inspection of welds, and with the precautions necessary to ensure the safety of operators. Copies may be had from the Institute of Welding, price 16*s*. inclusive of postage.

Welded Connections for Pressure Vessels

The stock of this IIW document, "*Recommended Connexions for Pressure Vessels*", is now nearly exhausted but there are a few copies left at 4*s*. 6*d*. each post free, obtainable from the Institute of Welding.

The report deals with carbon steel pressure vessels welded manually by the metal-arc process, and consists of an introduction with about 80 drawings, arranged in six sections, which deal respectively with screwed connections and screwed and studded connections, branches, flanges, jacketed vessels, tube to tube-plate connections and tube-plate to shell connections.

Brittle Fracture Tests

The Institute has recently published "*The Comparison of Brittle Fracture Tests*", being a report of Commission IX of the International Institute of Welding. This valuable report of a sub-commission of which Mr. W. Barr, O.B.E., of the United Kingdom, was the chairman, sets out the results of extended investigations of the results obtained on steels of varied composition subjected to six well known tests of notch ductility. The publication can be obtained from the Institute of Welding, price 5*s*. including postage.

NEWS OF MEMBERS

Metallizing Equipment Co. Ltd., of Chobham, Woking, have changed their name to METCO Ltd.

Mr. P. H. R. Lane, B.Sc.(Eng.), A.I.M., has been appointed the first Director of Research of the Drop Forging Association. He took up the appointment on 1st March. Mr. Lane has been with the B.W.R.A. for the past twelve years and was Head of the Members' Service Department before his resignation.

Mr. E. J. Keefe, B.Sc.(Eng.), has been appointed Welding Engineer to Cochran & Co., Annan, Ltd.

J. Morton, G.I.Mech.E., A.M.Inst.W., has taken up a new appointment as Assistant Works Manager with Messrs. Whessoe Ltd. of Darlington.

A. S. Bartlett, M.Inst.W., has been appointed Managing Director of Milford Docks and Dry Dock Companies.

CONTRIBUTORS TO THE JOURNAL

J. W. Addie, B.Sc.(Eng.), A.M.Inst.W., is with Associated Electrical Industries Limited, Transformer Division.

He was educated at Lenzie Academy and at Glasgow University, graduating with honours in 1942. Following a college apprenticeship with Metropolitan-Vickers Electrical Co. Ltd. he joined the Welding Engineering Department of that Company and was engaged

in the development of the inert-gas tungsten-arc process and on the application of resistance welding processes.

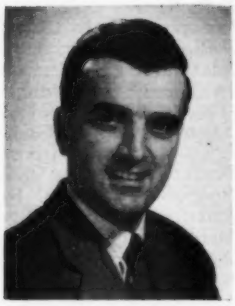
Since 1945, he has been concerned mainly with new projects in the design and manufacture of welding electrodes with his present Company in its Heating and Welding Department.

Dr.Ing. F. Busse is President of Peco Elektrische Schweissmaschinenfabrik Rudolf Bocks, München, Germany. He studied General Machinery Sciences at the Technische Hochschule at Braunschweig, where he graduated in 1924 as Diplom-Ingenieur and in 1927 as Doktor-Ingenieur. He was then engaged as mechanical engineer with several companies, and later was appointed staff member and director. From 1931 to 1934 he was active in the U.S.A. In all the positions he has held he has been particularly interested and concerned with welding problems, machines, and processes.

F. Busse

D. J. N. Laurie

C. Pfeiffer



R. S. Smith

Since 1946 Dr. Busse has been President of Peco Elektrische Schweissmaschinenfabrik Rudolf Bocks, one of the oldest manufacturing companies for resistance welding machines in Europe. He is a member of Verein Deutscher Ingenieure and Deutscher Verband für Schweisstechnik.

D. J. N. Laurie joined the Gas Light and Coke Co. in 1934 at the age of 14, and remained there until 1940. During this period he studied at East Ham Technical College.

He joined the R.A.F. in 1940 and was concerned with the maintenance and servicing of air frames, spending just under three years in the U.K., and a similar period in India.

After the war, Mr. Laurie joined Cyc-Arc Ltd. where he was engaged in the production and testing of stud welding equipment. Between 1946 and 1952 he progressed to the position of Assistant Developments Engineer, and dealt with development and research on stud welding equipment. In 1952 he took up an appointment as Developments Engineer with Cooke and Ferguson, who were producing Nelson stud welding equipment. After about a year he was transferred to Crompton Parkinson (Stud Welding) Ltd. and in 1960 he was appointed Chief Engineer.

Claes Pfeiffer, who was born in 1928, was educated at the Royal Institute of Technology, Stockholm, and graduated as a metallurgist in 1953. After graduation he joined Elektriska Svetsnings AB (ESAB), Gothenburg, as research metallurgist. In 1957 he became Chief Metallurgist, and in 1959 he joined AB Atomenergi (Atomic Energy Company), Stockholm, as research metallurgist, a position which he still occupies.

Rowland Sydney Smith is an Experimental Officer in the Metallurgy Department of the National Gas Turbine Establishment.

He was born in London in 1923. He obtained a Higher National Certificate in Electrical Engineering at Wimbledon Technical College in 1942, and then entered Government Service at the Royal Aircraft Establishment. In 1951 he moved to the National Gas Turbine Establishment where, after a period spent on the design of test equipment, he is now responsible for the high-temperature creep, fatigue, and general mechanical test facilities in the Metallurgy Department.

W. E. Stanton was educated at Wednesbury in Staffordshire, where he studied Metallurgy at the County Technical College. In his first appointment, with a Midlands foundry, he was engaged for two years on the production of precision metal patterns and prototype castings. Seeking more fundamental

knowledge, he joined the Patent Shaft Steel Works in the capacity of Chemical and Metallurgical Laboratory Assistant. Three years later, in 1934, he accepted the post of Chemist-Metallurgist to Messrs. J. B. & S. Lees, a Midlands firm engaged in the hot and cold rolling of steel strip. Finally, he joined the Technical Staff of Metallisation Limited in 1937, with whom he has since held various positions, including those of Chief Inspector, Development Engineer, Production Manager, and more recently Technical Manager.

SCHOOL OF WELDING TECHNOLOGY

Non-Destructive Weld Examination

The feature of the School of Welding Technology's fourth course on this subject was a special exhibition of equipment available in this country. The exhibition was held in the Large Hall at the Surbiton Assembly Rooms, and enabled course members both to see the latest equipment and to discuss individual problems with the manufacturers' staff in attendance.

Eight stands showed equipment for radiographic weld inspection, but for safety reasons it was obviously not permitted to give practical demonstrations. In the case of gamma-ray machines, containers for different radiographic sources were shown, with remote control devices for panoramic exposures. There were several X-ray units, illustrating all that is best in standards of mobility and control, and one firm showed the xero-radiograph of an aluminium weld: this consisted of a specially developed re-usable plate, viewed under indirect lighting.

An unusual instrument which created much interest was a leak detector, designed to determine accurately the leak rate from a system. The instrument utilizes a tracer gas, and registers its presence by measuring the optical absorption in the infra-red spectrum by means of a gas analyser. Among more well known methods of weld inspection, the magnetic crack detector was shown in operation by two or three companies, and a variety of dye penetrant, fluorescent, and magnetic fluids were demonstrated.

Ultrasonics was represented by three companies, and the great interest shown indicated the controversy that still exists over its application to weld testing. Sample welds were provided, enabling the traces on the cathode-ray tubes to be compared with radiographs.

The demonstrations were preceded by a session in which representatives described the range of equipment their companies produced, and indicated any special features of that on display. In the audience were 50 metallurgists, managers, welding inspectors, and engineers from 33 companies throughout the country, who earlier in the week had received lectures from leading experts on the physical principles of the main inspection methods and their detailed application to weld testing.

Among the companies taking part in the exhibition, which was organized by

Exhibition of non-destructive testing equipment

the School of Welding Technology, were:

Associated Electrical Industries Ltd., Scientific Apparatus & X-ray Department.
Brent Chemical Products Ltd.
Gamma-Rays Ltd.
The Infra Red Development Co. Ltd.
Kodak Ltd.
Manchester Oil Refinery (Sales) Ltd.
Pantak Ltd.
Pantatron Ltd.
Research & Control Instruments Ltd.
R.P.R. Patents Ltd.
S. Smith & Sons (England) Ltd.
Solus-Schall Ltd.
Ultrasonoscope Co. (London) Ltd.
Watson & Sons (Electro-Medical) Ltd. Industrial Division.

BRANCH NEWS

Birmingham — Brazing

At the meeting on 13th January a paper on "*Designing for Brazing*" was presented by Mr. N. H. Jones, Vice-Chairman of the Branch, and a Senior Engineer in the Joining Processes Department of the Joseph Lucas Group Research Centre. Among his activities is that of advising designers throughout the Lucas Organization on the use of brazing and other joining processes. This function was the basis of his lecture, presented to some 60 members and visitors.

Mr. Jones opened by discussing the factors that all methods of brazing have in common and followed this by describing the unique features of the various methods, ranging from torch to vacuum brazing. He emphasized the need for a designer to select the method for a particular application at an early stage in the design, so that the necessary features can be provided. Design features that aid inspection and simplify or eliminate jigging were described.

The lecturer pointed out that most metals could be brazed, as anyone who had attempted to use an 'unbrazable' material for a support jig would have found out.

He regretted that brazing processes were often selected to suit existing plant without regard for other work of a similar nature that was also being assembled by a second-rate method. The economy which could be effected by a change of process when all of the work was considered often compensated for the cost of new equipment. One of the many excellent slides used showed how an expensive machined component was redesigned to permit the furnace brazing of a number of simple pressed parts. In this particular instance, a further saving was effected in that small type changes could be incorporated in one part of the fabrication, the rest remaining standard.

Finally, the lecturer described several interesting brazing applications which illustrated both the design of complicated components and development of new brazing techniques. One assembly which involved over 4,000 brazed joints was successfully brazed in spite of the fact that a technique had to be developed and a special furnace built at extremely short notice.

As often happens, time limited what would otherwise have been an active discussion, but as Mr. Jones had already invited the audience to raise any points they cared to discuss during his lecture, the subject was adequately covered.

In the absence of Mr. K. H. Purdey, the Branch Chairman, the speaker was introduced by Mr. W. D. Waller and the vote of thanks was proposed by Mr. G. C. W. Read.

East Midlands — Electroslag welding

On Tuesday, 13th December, 1960, at the Welbeck Hotel, Nottingham, a paper was given by Mr. W. K. B. Marshall on "*Electro-slag Welding*".

The lecturer opened by saying that the process was very novel. It originated 10 years ago in the U.S.S.R. at the Paton Institute and only recently had it been introduced in the West.

Many slides were shown of the electro-slag machine and of very heavy plate being welded.

Mr. Marshall made it very apparent that the electro-slag fully automatic process has many advantages over conventional methods of welding; production time can be rated in hours instead of days with less welding labour; the deposition rate is of the order of 40–50 lb per hour per electrode with very high thermal efficiency, which allows outstanding economy in welding power consumption.

The welds are made in the vertical position in a single pass and no slag removal or surplus flux recovery equipment is needed. Distortion difficulties, which occur with conventional processes, are eliminated because the slag welding technique provides homogeneous heat distribution throughout the depth of the weld.

By the use of electro-slag welding, medium heavy forgings can be joined to make a single unit where the price of a heavy forging would be prohibitively high.

At the conclusion of the lecture many questions were asked on such matters as local normalizing of the welds, permissible misalignment, impact qualities, and the weld grain structures. Mr. Marshall dealt with all the questions very thoroughly.

Mr. H. Smales-Cresswell proposed the vote of thanks saying that Mr. Marshall's lecture had been very educational and he had given us much to think about for further uses of electro-slag welding. He felt that in the near future, we should be seeing this process in many new forms.

H.S-C.

East of Scotland — Welding of pipelines

The fourth meeting of the 1960–1 session was held at 25 Charlotte Square, Edinburgh, on 18th January, when Mr. R. J. Wright, Director of the Lincoln Electric Co. Ltd., presented a paper on "*Pipeline Welding*". The lecture was well attended by local members and friends, and quite a number from further afield.

Our speaker commenced his talk from the historical aspect and informed us that pipelines transportation went back as long ago as 7,000 years when bamboo, clay, hollowed rock and sewn ox-hides were used. Later, in 1861, an oil pipeline was made of wood; in 1865 one was made of cast iron; and then in 1910 came the steel pipeline.

From this date onwards the oil industry has been responsible for the boosting of steel pipelines, and in America by 1930 hundreds of thousands of miles of pipeline were being used to carry refined products as well as oil.

Mr. Wright explained how in the beginning the standard and efficiency of

the welding operators depended entirely on the welding engineer on the site. As time went on it became apparent that a definite standard had to be maintained and in about 1940 the A.S.M.E. code came into being. Subsequent amendments have been made and other codes have been formulated.

The lecturer then described improved welding techniques and specifications, better electrodes and bigger projects, as well as methods of testing welds mechanically and by non-destructive examination.

This talk was particularly interesting to the listeners, for at the present time Scotland's Gas Supergrid pipeline is still going ahead; unfortunately a scheme for a pipeline between Glasgow and Edinburgh, for the carriage of oils and certain solids, has been shelved temporarily although in a few years time it will become a necessity. A considerable number of technical points were mentioned by Mr. Wright in his lecture, which was followed by a lively discussion beneficial to all present.

A vote of thanks was extended to the speaker for his excellent lecture, which was heartily appreciated by all.

B.T.

Manchester — More pipelines

On Wednesday, 4th January, 1961, members and visitors heard a lecture entitled "*Pipeline Welding*", given by Mr. R. J. Wright, A.M.Inst.W., M.S.M.A.

The speaker commenced by saying that it is well known that transportation costs are one of the major problems facing industry as a whole and this is particularly true in the petroleum, petrochemical and gas-producing industries, where further development will be largely dependent upon the prices of their products when they reach the consumer. There can be no doubt that pipelines can mean lower transportation costs.

Mr. Wright described in detail the early history of pipeline transport. The inventive Chinese are believed to have used bamboo pipes as much as 7,000 years ago. In the Middle East a long-distance trans-desert pipeline made of sewn ox-hides, and designed to supply water to the armies of Cambyses, King of Persia, in his invasion of Egypt, was laid as long ago as 525 B.C. Probably the first oil pipeline was constructed in Pennsylvania in 1861; it was made of wood and was about 6 miles long. The first really successful pipeline, made of cast iron, was laid in 1865. When steel began to replace cast iron in 1910, there were 40,000 miles of pipeline in operation in the U.S.A.

In the United Kingdom the arc welding of pipelines was somewhat slower in developing, due undoubtedly to the fact that most commodities adaptable for transportation by pipeline could easily be moved by road tankers and that our major pipeline network, used for the transportation of coal gas, was constructed of cast iron pipes. It was the great success of welding during the war of such projects as 'Pluto', coupled with the immediate post-war expansion of the British petroleum industries and Gas Board undertakings, that really brought about the progress of welded construction in the United Kingdom to its present-day importance.

The lecturer then dealt with the efficiency of the operator and the welding engineer in the field, and it was said that the close co-operation between electrode manufacturers, the petroleum companies, gas boards and other large institutions has meant today there is no difficulty in obtaining highly skilled welders for pipeline work. Details were given of the training of welders in the correct techniques, such as overcoming one of the major problems in the welding of a pipe joint, *viz.* pinholes in the root run, by the setting of correct root gaps and introducing the use of small gauge electrodes using a weaving technique. Mr. Wright then went on to tell of the faster welding methods and the well established American procedure known as 'stovepipe welding'. The name 'stovepipe' is rather a misnomer for it has nothing to do with stove pipes; it is really a method of laying, that is, one pipe continually being added to the other, making each joint a positional weld. In practice, the welding procedure is to weld downward from 12 o'clock to 6 o'clock, and reverse to the accepted method, which is to weld upward from 6 o'clock to 12 o'clock. Welding data for typical pipe joints were given and illustrated by slides and diagrams.

Finally, a first-class film was shown of the welding of a pipeline at the Atomic Research Station at Winfrith Heath, Dorset. Particularly good were the excellent underwater pictures of the line being laid on the sea bottom after welding.

A.C.M.

North London — Practical CO_2 Welding

At the meeting of the Branch on 25th January Mr. F. Collins was to have spoken on "*Practical aspects of CO_2 welding*". In his place, and at *very* short notice, Mr. Arthur Smith of the British Welding Research Association stepped into the picture, to give a most excellent lecture on this subject. He supported his lecture with slides, and did full justice to the subject, dealing most ably with the many questions provided by the large gathering of members and visitors. The visitors came from manufacturers of this type of equipment, such as B.O.C., Lincoln Electric Co. Ltd., Murex, and Philips, from the user side Vauxhall Motors, Kelloggs, Wm. Press, A.P.V., Hawker Siddeley, N.P. Co.; from Paddington Technical College, and from Inspection bodies. A well earned vote of thanks was given by the Branch Representative for what proved to be a most instructive evening.

R.B.W.

South Western — Annual Dinner

The Branch Annual Dinner held at the Grand Hotel, Bristol, on 9th December, 1960, was again well supported by nearly 100 members and their guests. Mr. T. M. B. Sessions presided, the principal guests being Mr. I. E. King, C.B., C.B.E., M.R.I.N.A., R.C.N.C., Director of Dockyards Admiralty, and Mr. J. Strong, M.A., Past President of the Institute.

The Loyal Toast "H.M. The Queen" was proposed by the Branch Chairman.

In proposing the toast of "The Institute of Welding", Mr. King compared working conditions in the Dockyards as they were during his apprenticeship in the First World War with those existing today, and thought that the much improved conditions were due mainly to the wide application of welding in ship construction. Mr. King also paid tribute to Mr. A. J. Francis, President and founder member of the South Western Branch under whose guidance the Branch had prospered and its membership increased from 40 to 250.

Mr. Strong responded with an exhilarating and witty speech in which among other things he commended the activities of the Branch.

Mr. Peter Gardiner, first Branch Chairman, then proposed the toast of "The Guests" and concluded his remarks with mention of the useful investigations into the many varied aspects of welding being carried out by B.W.R.A. In response, Dr. R. Weck, Director of Research, B.W.R.A., thanked him for his kind remarks.

Gas shielded welding

On Monday, 9th January, at Radiant House, Bristol, Mr. A. A. Smith of the B.W.R.A. presented his talk on "*The Future of Gas Shielded Welding*".

Mr. Smith commenced with a brief description of the major advances made since the early days of bare wire welding and stressed the importance of the introduction of gas shielded welding. The highlights of the last ten years' development in tungsten-arc and consumable-electrode welding were mentioned. In tungsten-arc welding the importance of electrode polarity and the special techniques of a.c. welding were described. This was followed by mention of the special applications of tungsten-arc spot welding. In the field of tungsten

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arcs the major importance of the constricted arc was thoroughly discussed. The advantages of consumable-electrode welding were then considered in some detail with special reference to arc characteristics at low current and at very high current. Metal transfer studies at low current were described, together with the importance of wire diameters and fine wire guns. The constricted arc and its appearance in high-current welding of aluminium, and theories concerned with this were described. The metal transfer characteristics of steel wires in CO_2 shielding were considered and the special requirements of power sources for short-circuit arcs were detailed. The jetting of constricted arcs at high currents was related to the volt-amp curve.

The prospects for using all these new developments in the future were then considered by examining a number of slides depicting developments seen by the lecturer during his American tour. Each application was considered from the prospects this would hold for the future. The developments of these new arc processes would be valuable only if automation and mechanization were to increase, when the jig and tool developments and transfer machines would have to be equally developed. The lecturer thought more fundamental work should be done on arcs so that the processes going on in an arc could be fully controlled. He hoped a controllable section plasma would prove a universal tool for cutting and welding. A high-speed cine-film was then shown of free flight material transferred at short circuiting arcs in CO_2.

In a lively discussion conducted in Mr. Smith's inimitable down-to-earth style, he further elaborated on the 'constricted arc' and dealt with such practical topics as a method of argon tungsten-arc welding thin aluminium condenser tubes into thick aluminium alloy end plates. In proposing a vote of thanks, heartily endorsed by those present, Mr. E. M. Wilson congratulated Mr. Smith on his fine lecture and also expressed appreciation to Mr. A. G. Brain of B.W.R.A. for kindly operating the cine projector and showing the slides under adverse conditions.

E.M.W.

West of Scotland

Welding high-strength steels

On 18th January a paper was presented by Mr. L. H. Liston, on "*Welding and Design in the Fabrication of High Strength Steels*". The author dealt with the three factors governing the extent to which high strength steels can be applied at present:

(i) Design criteria as specified by present standard codes
(ii) Fabrication difficulties
(iii) Cost of the steel itself.

A quenched and tempered steel was the best high strength weldable steel available, combining high yield and ultimate strengths with good notch ductility, and Mr. Liston used this steel as an example in describing circumstances where a high strength steel was economically justified even without a change in design principle. The examples covered structures where much of the load was due to the steel itself (long-span road bridges); vessels subject to static loading, where the reduction in thickness achieved may eliminate the need for stress relief; and mobile applications where the reduction in dead weight could pay dividends. It was considered that the inherent toughness of the quenched and tempered steel was a valuable safeguard against the risk of brittle fractures where stress relieving was not possible, as in large structures.

In fabrication, it was necessary to form plates cold, or at the tempering temperature, and slight preheating was desirable when gas cutting thicker plates. For welding, a balance had to be maintained between enough heat to avoid weld cracking, but not so much as to cause overheating of the plate with consequent loss of notch ductility, or even of yield and ultimate strength in areas adjacent to the weld, but such control was practicable in manual welding. Automatic welding could be employed, but the heat input limitations generally rendered these methods more expensive than manual welding.

An interesting discussion ensued, with much additional data being given in the author's replies, and the meeting closed with a vote of thanks to Mr. Liston.

J.E.R.

BRITISH WELDING RESEARCH ASSOCIATION

Mr. R. P. Newman, A.M.I.Mech.E., has been appointed Head of the Members' Service Department of the Association in succession to Mr. P. H. R. Lane, who has been appointed Director of Research of the Drop Forging Research Association.

Mr. T. R. Gurney, M.A., A.M.I.C.E., will succeed Mr. Newman in charge of Fatigue Researches at Abington.

INTERNATIONAL INSTITUTE OF WELDING

Annual Meeting of Commission Chairmen

Between the Liège (Belgium) Annual Assembly in June 1960, and the New York (U.S.A.) Annual Assembly in April 1961, the Annual Meeting of Commission Chairmen of the IIW was held in Paris on 26th November, 1960. Mr. A. Leroy (France), Scientific and Technical Secretary of the IIW, presided at this Meeting, which was attended by Mr. W. Edström (Sweden), President of the IIW.

Co-ordination of the work of the Commissions

Discussion centred on a report prepared by the Scientific and Technical Secretary containing information necessary for the co-ordination of the work undertaken by the fifteen technical Commissions of the Institute and by their Sub-Commissions. In addition, special problems relating to the symbolization of filler products and to fundamental research on arc physics were examined.

Allocation of Work

On the basis of a list of welding processes prepared by the Scientific and Technical Secretary, certain processes, not yet studied by IIW Commissions, were allocated to various Commissions, as follows: Thermit welding, percussion welding, soldering with an iron (Commission I "Gas welding and allied processes"); condenser-discharge arc welding (Commission III "Resistance welding"). It was also proposed, firstly, that firecracker welding, arc welding with continuous bare electrode wire (unshielded), and arc welding with continuous covered electrode wire, processes which so far have fallen within the terms of reference of Commission XII "Special arc welding processes", be included in the programme of Commission II "Arc welding", and secondly, to ask Commissions I and XII to make suggestions as to the distribution of work on arc cutting and plasma jet cutting, cutting processes in general having, since 1956, been allocated in principle to Commission I.

The recommendations and proposals mentioned above will be transmitted by Chairmen to their respective Commissions for comment, with a view to final decisions being later taken by the Executive and Governing Councils of the IIW.

In the course of the discussion on the list of processes, the Chairman of Commission VI "Terminology" suggested the possible circulation, independently of the publication by the IIW of the sections of the "Multilingual Collection of Terms for Welding and Allied Processes", of lists of terms referring to new processes, drawn up with the collaboration of the Commissions concerned.

The Scientific and Technical Secretary agreed to the proposal made by the representative of the Chairman of Commission VIII "Hygiene and Safety" that the list might be used in carrying out, in accordance with a precise plan, investigations on the problems of safety in connection with each process.

Annual Assemblies

Commissions I and XI "Pressure

vessels, boilers and pipelines", having expressed the wish that colloquia similar to those held at Liège should be arranged for future assemblies, it was stated that the organization of colloquia, public sessions and lectures at Annual Assemblies would be considered in conjunction with the delegations of the host countries. It is proposed to hold, at the 1962 Assembly, with the collaboration of Commission XI, and possibly Commissions II and III, some such meeting on the theme of welding high-pressure pipelines and/or penstocks.

To enable members representing distant countries to attend Sub-Commission meetings which, until now, have only been held between Annual Assemblies, and so that members of Commissions with a very large attendance may carry out a greater quantity of profitable work during Assemblies, Sub-Commissions will be authorized, in certain circumstances, to hold meetings on the occasion of, and preferably immediately after, Annual Assemblies.

Recommendations have been made concerning the character and drafting of Commission resolutions and their presentation to the Governing Council at Annual Assemblies.

Information was given to Chairmen on the final programme for the next Annual Assembly in New York, in April 1961, on the arrangements for the transport of European delegates by aircraft chartered by the IIW, and on the steps taken by the IIW Secretariats to ensure that lists of Commission members attending the New York Assembly will be issued as soon as possible. Details were given of the thirteen papers to be presented by European members at the Annual Meeting of the American Welding Society (AWS) which follows the IIW Assembly: these comprise the "Adams Lecture", two "Educational Lectures" and ten papers to be presented at "Technical Sessions".

A proposal was made that, as well as the usual classification by country of literature shown at the exhibitions of publications at IIW Annual Assemblies, works on a given subject should be grouped together and that welding instruction should be adopted as a possible theme for 1962; this proposal will be examined by Commission IV "Documentation".

General Items

An amendment of the Constitution and Bye-Laws of the IIW, in connection with the terms of office of Commission Chairmen, was examined.

Whether the names of those making a special contribution to a document recommended for publication and drawn up by a Commission or Sub-Commission should be mentioned in the document was left to the discretion of the Chairman of the Commission concerned.

When Commission documents can usefully be summarized, Commission Chairmen should ask the authors concerned for brief summaries, drafted in the two official languages of the IIW, English and French.

CONFERENCES and EXHIBITIONS

AWS Annual Convention

The American Welding Society will hold its 42nd Annual Convention and Welding Exposition and will act as hosts to the International Institute of Welding, in New York, from 10th to 21st April, 1961.

Economics of pipelines

An all-day Symposium entitled "Economics of Pipelines" will be held by the Pipeline Industries Guild on Tuesday, 11th April, 1961, at Caxton Hall, Westminster. Three papers will be introduced. The meeting is open to all persons interested in the subject, and applications for tickets and the pre-printed papers should be made to the General Secretary, 7 Iddlesleigh House, Caxton Street, S.W.1. The inclusive fee will be £1 1*s*. 0*d*.

WELDING EXHIBITION

The Engineering, Marine, Welding and Nuclear Energy Exhibition is once again to be held at Olympia, from 20th April to 4th May, 1961.

For the second time, the Spring Meeting of the Institute has been arranged to coincide with the Exhibition, and the last afternoon, on Friday, 28th April, has been left free for members to visit Olympia. The official luncheon to Members of Council will also be given on that day.

Although the application of welding to almost all forms of engineering construction will be evident throughout the Exhibition, the displays of the welding equipment manufacturers will be grouped mostly in the Empire Hall as in previous years.

Many items of equipment that will be on display, or demonstrated, have been described in this section of *B.W.J.*; but there will also be many new features that have not before been shown publicly.

Visitors will find, as perhaps would be expected, that considerable attention has been given to the semi-automatic and fully automatic gas-shielded arc processes, particularly in relation to CO_2 shielding. New ideas and refinements of existing equipment will show that still greater control over the welding variables is being attained, so ensuring the sound quality of the final welds. This is particularly true in the resistance welding field.

No description of the items that are to be exhibited could equal the information that can be gained from a visit to the Exhibition and—more important—discussions with the representatives on the stands. But it is intended to review in subsequent issues of *B.W.J.* a selection of the more interesting equipment exhibited.

Structural processes in creep

The Iron and Steel Institute and the Institute of Metals are holding a Joint Symposium on Structural Processes in Creep, as part of the Annual General Meeting of the ISI. The meeting will be held at the Hoare Memorial Hall, Church House, London, S.W.1, on 3rd–4th May, 1961.

The Institute's Presidential Address will be delivered by Sir Charles Goodeve, O.B.E., F.R.S., on the morning of 3rd May.

NEWS FROM INDUSTRY

Drop Forging Research Association

As mentioned under "News of Members" the Council of the Association has appointed Mr. P. H. R. Lane as first Director of Research.

The offices of the Association are at Hoyle Street, Sheffield 3 (Tel.: Sheffield 28941).

Mond Nickel

The Mond Nickel Company Ltd., an affiliate of the International Nickel Company of Canada, Ltd., has changed its name to The International Nickel Company (Mond) Ltd.

The change of name will serve to identify the Company more closely with the Canadian Company and the U.S.A. affiliate, and will indicate the international nature of the Company's activities.

NEW PLANT AND EQUIPMENT

Time indicator

A series of compact, electro-chemical, elapsed time indicators have been introduced by Industrial Instruments Ltd., for the recording of the total operation time of electrical equipment.

These new indicators, known as the Selachron range, have been designed in forms suitable for either a.c. or d.c. operation and in sizes for use with voltages of from 6 to 300 volts.

Portable blast cleaner

A completely self-contained portable blast cleaning unit, no bigger than a small hand vacuum cleaner, is being produced by Hodge Clemco Ltd., Sheffield.

Known as the Educto-o-Matic, it weighs only seven pounds and contains its own vacuum pick-up and dust extraction unit so that the only connection required is to an airline which

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The machine is small enough to fit through tank manholes and is suited for small jobs that can be cleaned without dismantling. The blast head can be swivelled for use at any angle.

The abrasive is continuously recirculated so that there is very little wastage. A full charge of four pounds will normally blast for 15 to 40 min, according to the skill of the operator.

X-ray analysis

A brochure, List 177/2, recently published by Cambridge Instrument Co. Ltd., gives a comprehensive description of the construction and operation of the Microscan X-ray analyser. This is an emission type of instrument, capable of providing a detailed analysis of small regions of about 1μ dia. on sample surfaces. It also incorporates a deflection system so that areas of about ½ mm square can be scanned.

The equipment described is versatile yet simple to use. In addition to the X-ray microanalyser it includes a built-in optical microscope, and can give simultaneous electron and X-ray images for comparative purposes.

Point-by-point microanalysis to an accuracy of $\pm 0{\cdot}1$ to $\pm 1{\cdot}0\%$ can be obtained with a resolution of 1μ.

Mild steel electrodes

NuFive and NuSeven are two mild steel electrodes which were introduced at the end of last year by the Lincoln Electric Co. Ltd.

The first is an all-positional cellulosic type of electrode to Class E.111 of BS.1719, and is particularly suitable for pipe welding.

The second electrode is of the high deposition, iron-powder rutile type, E.917, and is suitable for general applications. It gives about 30% more weld deposit than standard E.317 types of electrode.

Both electrodes have been approved by Lloyd's Register of Shipping and the Ministry of Transport for welding mild steel in all positions.

Powder weld hard-facing

At the Institute's Spring meeting in Droitwich last year brief details were given (*B.W.J.*, May, p. 322) of the technique of powder welding, by which cobalt-based Stellite alloys are sprayed in powder form and fused simultaneously with the base material.

A special 'powder weld' has now been developed by Deloro Stellite Ltd. in collaboration with the Schori Division of F. W. Berk & Co. Ltd., and the process will be publicly demonstrated for the first time at the Engineering, Marine, Welding and Nuclear Energy Exhibition.

Multi-purpose torch

A Harris-designed universal pressure torch is now in production at the Enfield Works of British Industrial Gases. It can weld, cut, heat, flame clean, gouge, and rivet wash using acetylene, propane, butane, hydrogen or town gas as the fuel supply, and at low, medium or high pressures.

Like other torches designed by the Harris Calorific Organization, Model 43 gives high fuel savings when operated on low-pressure, for the full cylinder contents can be used. The torch head can be swivelled so as to allow operations to take place in any position, and there is a wide range of flame ratings for each of the nozzles supplied.

Lightweight cutting torch

The Firefly ultra-lightweight BOC cutting torch, which was previewed at last year's motor shows is now generally available. The torch weighs only 12 oz. but it can cut mild steel up to ¾ in. thick. Nozzles will at first be available only for use with acetylene but a range of propane nozzles will later be introduced. The gases are fed through separate supply tubes to the nozzle, so that the risk of backfires is avoided. Trimming valves are mounted ahead of the hand grip for easy control.

CORRECTION

Computor Controlled Cutting

In the note on the new BOC 'Eagle' computor-controlled gas cutting machine (*B.W.J.*, February, p. 72) it was erroneously stated that a second machine was to be delivered to Harland & Wolff Ltd. This second machine, now almost complete, is to be installed at the Barrow-in-Furness yards of Vickers-Armstrong (Shipbuilders) Ltd.

We apologise to the companies concerned for publishing this misleading information.

Cover illustration

The first machine, undergoing works acceptance trials at Edmonton, is shown in our front cover illustration.

DIARY

4th April—East Midlands—Annual General Meeting and films (Nottingham)
North London (Slough Section)—"*Electrical Characteristics of Welding Plant*" by J. C. Needham (Lecture Room, Community Centre, Farnham Road, Slough, 7.30 p.m.)

5th April—Manchester—Annual General Meeting and film show (Reynolds Hall, College of Science and Technology, Manchester, 7.15 p.m.)

10th April—N.E. Tees-side—Annual Meeting and Chairman's Address (Cleveland Scientific and Technical Institution, Corporation Road, Middlesbrough, 7.30 p.m.)
South London (Medway Section)—Annual General Meeting (Sun Hotel, Chatham, 7.30 p.m.)
South Western — Annual General Meeting and films (Radiant House, Bristol, 7.15 p.m.)

11th April—Liverpool—Annual General Meeting and films (College of Technology, Byrom St., 7.15 p.m.)
Pipeline Industries Guild—All day Symposium on "*Economics of Pipelines*" (Caxton Hall, Westminster)

11th–14th April—Battersea College of Technology—Vacation Course on Fracture of Metals (Metallurgy Dept.)

11th–19th April—International Institute of Welding—Annual Assembly (New York City)

12th April—East of Scotland—Annual General Meeting (25 Charlotte Square Edinburgh, 7.30 p.m.)
South London—Technical Film Meeting, followed by Annual General Meeting (54 Princes Gate, S.W.7)

13th April—N.E. Tyneside—"*Computor controlled cutting*" by R. Sillifant (Mining Institute, 7.0 p.m.)
Southern Counties—Annual General Meeting and technical film (Technical College, Southampton)
Eastern Counties—Annual General Meeting.

14th April—Birmingham—Annual General Meeting and technical films (Grand Hotel, Birmingham, 7.30 p.m.)
Wolverhampton—16th Annual Dinner and Ladies' Night (Wulfrun Hall)

17th April — Wolverhampton — Annual General Meeting (Wulfrunians Club, 7.30 p.m.)

18th April — Leeds — Annual General Meeting (Hotel Metropole, Leeds, 7.30 p.m.)

19th April—West of Scotland—Annual General Meeting and film night (Institute of Engineers & Shipbuilders, Glasgow C.2, 7.0 p.m.)

20th April–4th May—Eng. Marine, Weld. & Nuc. Eng. Ex. (Olympia)

21st April—Liverpool—25th Anniversary of Foundation of Branch, Annual Dinner to entertain the Lecturers (Victoria Hotel, New Brighton, 6.30 for 7.0 p.m.)

24th–27th April—Inst. Physics and Phys. Soc.—Conference on "*Mechanics of Rupture*" (Southampton University)

25th–28th April—Institute of Welding—Spring Meeting. "*Recent Developments in the Welding and Allied Processes*" (54 Princes Gate, S.W.7)

26th April — North London — Annual General Meeting (54 Princes Gate, S.W.7, 7.30 p.m.)

27th April—London Branches—Joint Annual Dinner (Quaglino's Restaurant, 7.0 for 7.30 p.m.)

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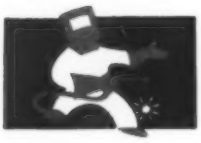

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Current WELDING LITERATURE

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CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

African Oxygen (South Africa), 1960, vol. 5, December

Purging gases the safe way (13)

Quality light-gauge welding with short arc, V. J. D. Hill (19–25)

Canadian Welder, 1960, vol. 51, October

Welded rigid frame office building (8–10)

Testing welding procedures and operators, A. S. Thomson (12–14)

R.C.N. ships X-rayed (16)

Extreme cleanliness standards maintained in fabricating stainless steel liquid oxygen vessels (18–19)

Canadian Welder, 1960, vol. 51, December

North America's first T-1 welded penstocks (8–9)

Friction welding studied (10–11)

Welded crane carrier chassis, E. Thibodeau (12–13)

Welded ferry boats (16)

(*Philips*) *Welding News* (Holland), 1960, No. 114, September

Processing of 5% chromium–0·5% molybdenum steel, C. Nederveen (3–7)

Application of tubular girders in welding structures at Messrs. La Maquinista Terrestre Y Maritima, S.A., A. G. Canals and C. R. Rosello (8–14)

Automatic welding, J. W. A. Stemerdink (15–16)

Przeglad Spawalnictwa (Poland), 1961, vol. 13, February

New trends in welding of modern high pressure steam boiler drums, S. Zaleski

Technical and economic problems of hard surfacing blooming mill rolls, S. Dobke

Evaluation of new methods of copper welding and possibilities of their application in Polish industry, J. Czech

Packet oxygen cutting in the workshop, R. Malentowicz

Influence of carbon on weldability of stainless chromium steels, J. Wegrzyn

Thermit fusion welding procedure in rail joining on Polish railways, L. Nekanda-Trepka

Schweissen und Schneiden (Germany), 1960, vol. 12, December

Index numbers for oxy-fuel gas flames for welding, K. Teske (507–513)

Manufacture and properties of atomized stabilized ferro-silicon 45% Si, K. Feldmann and K. Frank (514–517)

Tests on pipes with induction welded longitudinal seams, T. Furkel (517–525)

Inductive longitudinal seam-welding of tubes, D. Kronauer and M. Thiele (525–530)

Welded live rings for swivelling cranes, A. Buchholz (530–532)

Soudage et Techniques Connexes (Paris), 1960, vol. 14, November–December

Main properties and weldability of titanium and its alloys, R. Develay (409–420)

The welding of titanium and its alloys, R. Lachenaud (420–431)

The welding of galvanized steels, M. Evrard (437–448)

Pressure vessel brittle fracture and information required to design against it, A. A. Wells (449–454)

The construction of the Commerce bridge in Liège, H. Louis (455–466)

South African Institution of Welding Monthly Bulletin, 1960, No. 89, December

New techniques for measuring the hydrogen content of steels (2)

Why preheat? (2–4)

Welding and Metal Fabrication, 1961, vol. 29, January

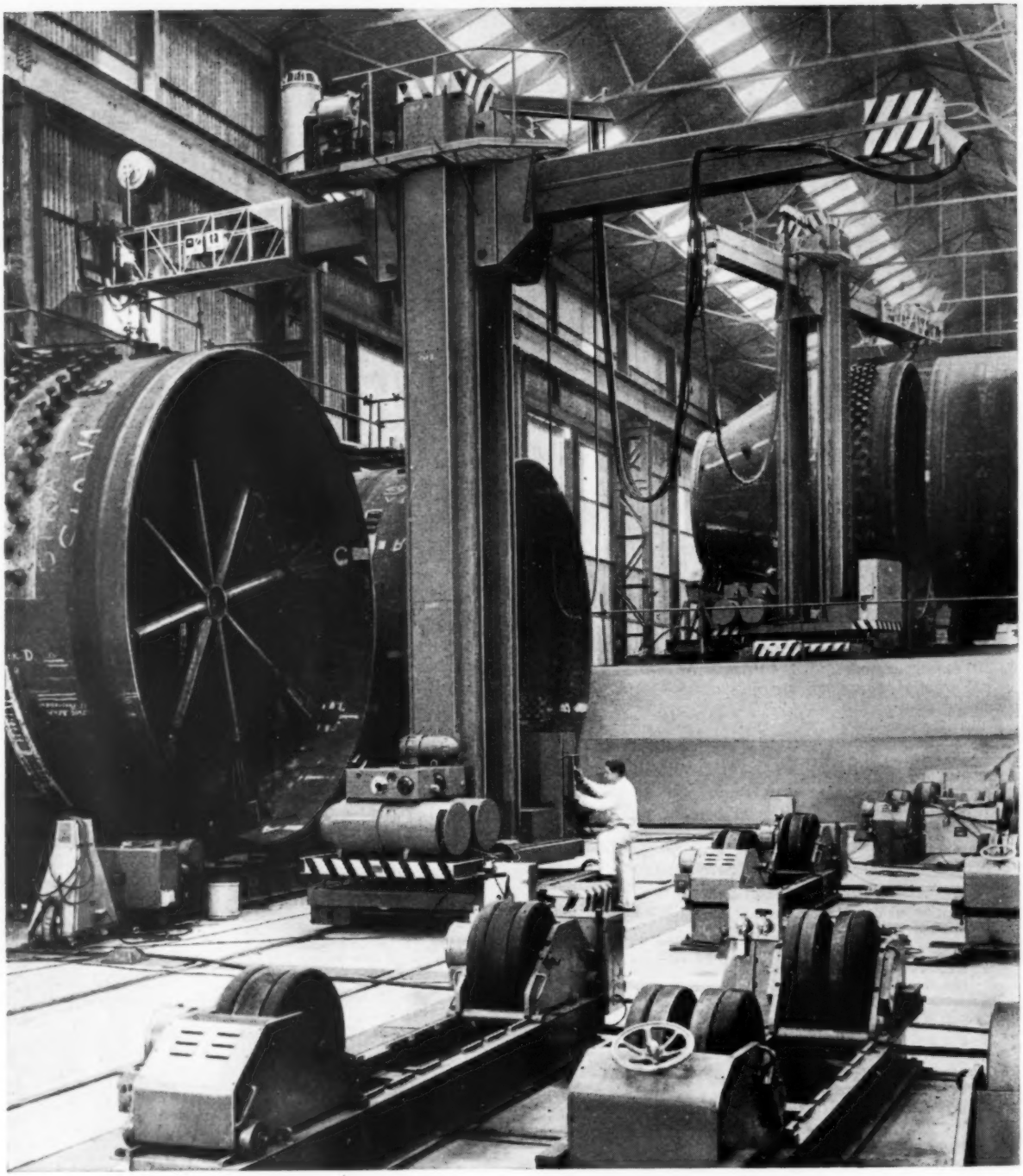
Oil storage tanks: a new approach to welding vertical seams, A. B. Fieldhouse (2–7)

Nuclear fuel handling equipment. Production of welded charge face machinery for Berkeley, T. J. Palmer (8–21)

Fusion welding of titanium and its alloys, W. G. Hull (24–31; 36)

Welding Engineer (U.S.A.), 1960, vol. 45, December

Plasma flame cutting of mild steel seen as competitive with oxy-fuel process, H. C. Phelps (33–36)



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Mig, submerged-arc join wind tunnel parts, S. J. Buell (37)

Welded nickel steel vessels withstand pressure, impact without stress relief (38; 40)

Tig welded insert ring helps increase pipe quality, C. H. Voelker (46–47)

Controlled angle Tig torch simplifies cabinet welding, F. M. Simms and J. V. Warinsky (50)

Welding Fabrication and Design (Australia), 1960, vol. 4, November

Silver brazing, M. W. McKinley (7–13)

Welding Journal (U.S.A.), 1961, vol. 40, January

Vapour-shielded arc welding at 200 ipm, R. A. Wilson (13–17)

Hard surfacing of blast furnace bells and hoppers is accomplished with the submerged-arc process, using iron- and nickel-base alloys, F. J. Gaydos and N. Fragasse (18–24)

Inert-gas spot welding in the aircraft and missile industry, R. L. Hackman (25–33)

Principles of template preparation for the oxygen cutting process, L. M. Layden (34–40)

Studies of hot cracking in high-strength weld metals, H. W. Mishler and others (1*s*–7*s*)

Properties of plasma-sprayed materials, M. A. Levinstein and others (8*s*–13*s*)

Electrode for spatter-free welding of steel in carbon-dioxide, E. Cushman (14*s*–21*s*)

Arc welding of a Ni–Cr–Fe (Inconel) alloy for nuclear power plants, J. Bland and W. A. Owczarski (22*s*–32*s*)

Application of 2219 aluminium alloy to missile pressure-vessel fabrication, C. H. Crane and W. G. Smith (33*s*–40*s*)

Brittle fracture characteristics of a reactor pressure-vessel steel, E. T. Wessel and W. H. Pryle (41*s*–48*s*)

Welding Production (U.S.S.R.), 1960, No. 2, February (Trans. B.W.R.A., January 1961)

The present state of welding engineering in the U.S.S.R. and the lines along which it should be developed, B. E. Paton (1–8)

Investigation of the properties of metal deposited by certain heat-resisting electrodes, F. I. Pashukanis and A. E. Runov (8–15)

The nature of metal transfer when welding with coated electrodes (investigation by the method of probes), A. N. Bykov and A. A. Erokhin (15–19)

A method of assessing quantitatively the liability of welded joints to cold cracking B. A. Kolodnaya (20–24)

Stresses and strains as influenced by the welding of Duralumin D16T, I. N. Artem'eva (25–30)

Properties of underwater arcs, T. I. Avilov (30–33)

Microstructures and strength of pressure welded joints in clad steels, E. I. Astrov (33–39)

Vibro-arc hardfacing under flux, V. V. Shliapin and others (39–43)

New compositions of weldable chromium–nickel–niobium austenitic wire, Z. I. Kopelman-Serpukhova and others (43–47)

Automatic welding of press-dies with powder wire in CO_2, M. I. Razikov and E. I. Bobrov (47–50)

Bath arc welding flanges with CO_2, A. E. Akulov and V. V. Spitsyn (50–52)

Improved mixtures for wear-resistant hardfacing, I. I. Iskol'dskii and S. L. Cherkinskaya (52–57)

The electrical conductivity of welded joints in copper, L. E. Fedotov (57–60)

A plant for automatically hardfacing rolling stock bogie thrust bearings, Yu. G. Chursin (61–62)

The adhesive bonding of metals, G. Schwartz (64–70)

Review of the general machine construction time norms for automatic, semi-automatic and manual arc welding, A. D. Gitlevich (71–75)

Welding Research Abroad (U.S.A.), 1961, vol., 7 January

Brittle fracture of notched tensile specimens. Abstract of "Rupture fragile d'eprovettes entaillees sollicitees par traction" by R. Dechaene and others. Translated by G. E. Claussen (92–95)

Other Journals

Recent and current developments in electric arc welding, W. A. Wrate (*The Production Engineer*, 1960, vol. 39, November, pp. 646–655)

The tungsten carbide rotary cutter, J. D. Snow (*The Production Engineer*, 1960, vol. 39, November, pp. 656–666)

Production of high strength bellows: methods of fabrication in Monel and stainless steel (*Metal Industry*, 1960, vol. 97, November 18, pp. 423–424)

Welded cryogenic steel takes impact, pressure (*Steel* (U.S.A.), 1960, vol. 147, November 7, pp. 108–109)

Progress in welding steels . . . vapour-shielded arc means faster welding, R. A. Wilson (*Metal Progress* (U.S.A.), 1960, vol. 78, October, pp. 96–99; 152; 154)

Progress in magnesium alloys, J. V. Winkler (*Metal Progress* (U.S.A.), 1960, vol. 78, October, pp. 146–148; 158; 160)

Materials and process applications in the automotive industry, M. F. Garwood (*Metal Progress* (U.S.A.), 1960, vol. 78, October, pp. 115–129)

Progress in aluminium alloys (*Metal Progress* (U.S.A.), 1960, vol. 78, October, pp. 137–142)

Welding processes, J. J. Chyle (*Mechanical Engineering* (U.S.A.), 1960, vol. 82, May, pp. 43–47)

Welding in Russia (*Metallurgia*, vol. 62, November, pp. 181–182)

Cranes help to make cranes at a new plant, J. A. Weller (*Canadian Machinery and Metalworking*, 1960, vol. 71, October, pp. 102–104)

Tape control and spot welding combine to produce problem parts (*Canadian Machinery and Metalworking*, 1960, vol. 71, pp. 168–170)

Longer wear life with right hardsurface rod (*Canadian Machinery and Metalworking*, 1960, vol. 71, October, pp. 170)

Radiographic testing examines the depths, P. W. Sherwood (*Canadian Machinery and Metalworking*, 1960, vol. 71, October, pp. 172, 174)

Quenched arc cutting of honeycomb materials (*Machine Shop Magazine*, 1960, vol. 21, November, pp. 684–686)

Mechanized welding line for open-web steel joists (*Machine Shop Magazine*, 1960, vol. 21, December, pp. 734–738)

Radioisotopes broaden field for non-destructive tests, R. Hamlin (*Iron Age* (U.S.A.), 1960, vol. 186, December 1, pp. 127–129)

Square butt welding costs less (*Iron Age* (U.S.A.), 1960, vol. 186, December 1, p. 139)

Arc welding equipment—Part 1, J. Latimer (*New Zealand Engineering*, 1960, vol. 15, October, pp. 378–380)

Introduction to ultrasonic butt weld testing, A. C. Rankin (*Pulse*, October 1960, pp. 2–9)

Lining steel tanks with plasticized P.V.C. (*Electroplating and Metal Finishing*, 1960, vol. 13, December, pp. 445–450)

Quenched arc process cuts honeycomb foil at high rate *Machinery Lloyd*, 1960, vol. 32, December 10, pp. 21–22)

Foil feeding device for high-frequency welding machines (*Werkstatt und Betrieb* (Germany), 1960, vol. 93, November, p. 701)

Simplified calculation of the fillet weld thickness at dead load, H. Gut (*Werkstatt und Betrieb* (Germany), 1960, vol. 93, November, pp. 723–727)

Russian hard facing process (*Commonwealth Engineer* (Australia), 1960, vol. 48, October, p. 48)

Welding dissimilar metals (*Metal Industry*, 1960, vol. 97, December 2, pp. 461–462)

Machine makes smooth cuts in honeycomb materials (*Iron Age* (U.S.A.), 1960, vol. 186, November 17, pp. 141–143)

Tungsten-arc welding torch cuts light-gauge metals (*Iron Age* (U.S.A.), 1960, vol. 186, November 17, pp. 152–153)

How to weld graphitic tool steel, C. A. Pfouts and C. F. Jatczak (*Steel* (U.S.A.), 1960, vol. 147, November 14, pp. 116–117)

Welding in steel construction, R. Weck (*Building with Steel*, 1960, vol. 1, No. 4, pp. 5–11)

Castellated construction (*Building with Steel*, 1960, vol. 1, No. 4, pp. 26–31)

Producing and testing bellows joints (*Engineering*, 1960, vol. 190, November 25, pp. 732–733)

Stress-corrosion failure of austenitic stainless steel, A. B. Chatterjea and B. R. Nijhawan (*N.M.L. Technical Journal* (India), 1960, vol. 2, August, pp. 20–25)

Design and construction of power station feed heaters, J. V. Bigg (*Proceedings of the Institution of Mechanical Engineers*, 1960, vol. 174, No. 7, pp. 293–311)

Modern aids in the design of railway bogies, A. W. Manser (*Proceedings of the Institution of Mechanical Engineers*, 1960, vol. 174, No. 8, pp. 363–367, Communications p. 368, Author's reply p. 369)

The strength of rails with particular reference to rail joints, S. Wise and others (*Proceedings of the Institution of Mechanical Engineers*, 1960, vol. 174, No. 9, pp. 371–407)

Pressure vessels for gas-cooled graphite moderated reactors, M. J. Noone and R. F. Bishop (*The Chartered Mechanical Engineer*, 1960, vol. 7, December, pp. 516–517)

Production procedures at the Beacon Works of John Thompson Motor Pressings Ltd. Part 3 (*Sheet Metal Industries*, 1960, vol. 37, December, pp. 870–885)

Western shipbuilder bites into gas market, G. E. Mortimore (*Canadian Machinery and Metalworking*, 1960, vol. 71, November, pp. 67–69)

The metalworking behind Canada's first nuclear power station. Part 4, J. A. Weller (*Canadian Machinery and Metalworking*, 1960, vol. 71, November, pp. 76–81)

This saw cuts pipe moving at 20 m.p.h., G. Coppa-Zuccari (*Canadian Machinery and Metalworking*, 1960, vol. 71, November, p. 83)

Short-arc welding pinpoints the heat (*Canadian Machinery and Metalworking*, 1960, vol. 71, November, pp. 108, 110)

Alberta hydro penstocks fabricated from Ti steel (*Canadian Machinery and Metalworking*, 1960, vol. 71, November, p. 112)

Welded tubing passes test for hydraulic line uses (*Iron Age* (U.S.A.), 1960, vol. 186, November 10, p. 180–181)

How to fabricate Rene 41, L. A. Weisenberg and R. J. Morris (*Metal Progress* (U.S.A.), 1960, vol. 78, November, pp. 70–74)

Brazing Rene 41, G. S. Hoppin (*Metal Progress* (U.S.A.), 1960, vol. 78, November, pp. 75–79)

Refractory metals for air and space vehicles, R. H. Gassner (*Metal Progress* (U.S.A.), 1960, vol. 78, November, pp. 80–87)

Progress with 25% nickel steels for high strength applications (*Metal Progress* (U.S.A.), 1960, vol. 78, November, pp. 99–100)

Brazing honeycomb (*Aircraft Production*, 1960, vol. 22, December, p. 452)

Solderless terminals (*Aircraft Production*, 1960, vol. 22, December, pp. 464–467)

Special fasteners for aluminium. Part 2, Bolt type fasteners, H. Hinxman (*Metal Industry*, 1960, vol. 97, December 16, pp. 495–497, 504)

Thin tube plates for h.p. heat exchangers, D. E. Hartley (*Nuclear Engineering*, 1961, vol. 6, January, pp. 8–11)

Rocket motor case material evaluation by pressure vessel testing, C. W. Haynes and P. J. Valdez (*Aerospace Engineering*, 1960, vol. 19, December, pp. 30–36).

Automatic ultrasonic testing of welds (*SS News on Non-Destructive Testing*, 1961, No. 19, January, pp. 12–15)

Welded tubes gain new markets (*Iron Age* (U.S.A.), 1960, vol. 186, November 3, p. 47)

Welders work with many arcs from a single power source (*Iron Age* (U.S.A.), 1960, vol. 186, November 24, pp. 96–97)

How heat contours metals (*Iron Age* (U.S.A.), 1960, vol. 186, December 8, pp. 118–119)

When weight creates a problem turn to chemical milling (*Iron Age* (U.S.A.), 1960, vol. 186, December 8, pp. 120–122)

How to weld columbium alloys (*Iron Age* (U.S.A.), 1960, vol. 186, December 15, pp. 110–112)

New controls spur spray brazing (*Iron Age* (U.S.A.), 1960, vol. 186, December 15, p. 118)

Machine solders automatically (*Iron Age* (U.S.A.), 1960, vol. 186, December 22, p. 68)

How friction welding joins bar stock and tubing, R. R. Irving (*Iron Age* (U.S.A.), 1960, vol. 186, December 29, pp. 47–49)

On the study of restraint and residual stress due to welding on erecting butt joints of ship's hull, M. Muto (*Journal of the Society of Naval Architects of Japan*, 1960, vol. 107, July, pp. 277–286)

A proposal concerning the automatic submerged-arc welding procedures of assemblies for ships' hulls, T. Yoshida (*Journal of the Society of Naval Architects of Japan*, 1960, vol. 107, July, pp. 293–302)

How to choose the right shielding gas, I. D. Holster (*Steel* (U.S.A.), 1960, vol. 147, December 12, pp. 78–81)

Continuous buttweld mill modernizes pipemaking (*Steel* (U.S.A.), 1960, vol. 147, December 12, pp. 86–90)

Automation speeds brazed heating units; quality up (*Steel* (U.S.A.), 1960, vol. 147, December 12, pp. 92–93)

New jobs sought for brazing platens (*Steel* (U.S.A.), 1960, vol. 147, December 19, pp. 106–107)

Inspection is the key to welded tubing acceptance (*Steel* (U.S.A.) 1960, vol. 147, December 19, pp. 110–111)

Spiral pipe machine welds inside, outside seams (*Steel* (U.S.A), 1960, vol. 147, December 26, p. 64)

The inspection of primary circuits and reactor pressure vessels of nuclear power plant, H. N. Pemberton (*Chartered Mechanical Engineer*, 1961, vol. 8, January, pp. 4–12)

Preparation of tags for soldering (*Tin and its Uses*, 1960, No. 50, pp. 10–12)

Arc welding equipment. Part 2, J. Latimer (*New Zealand Engineering*, 1960, vol. 15, November 15, pp. 421–424)

ADDITIONS TO THE LIBRARY

Books and Pamphlets

A. G. THOMAS and P. J. H. RATA: *Aluminium busbar*. A comprehensive handbook on the design, construction and installation of aluminium and aluminium alloy busbar. London, Hutchinson Scientific and Technical for Northern Aluminium Company Limited, 1960 (Price: 21*s.*)

IIW DOCUMENTS

Issued for Publication

The following documents have been issued by the IIW for publication, and may subsequently be published in the B.W.J. *Single copies of the duplicated text may be obtained immediately for a small charge from the Scientific and Technical Secretariat of the IIW, 32. Bd. de la Chapelle, Paris 18e.*

IIS/IIW-67-61 (Commission XIII "Fatigue Testing"): **"Fracture of a diesel engine connecting rod."**

IIS/IIW-68-61 (Commission XIII "Fatigue Testing"): **"Fracture of a web of a crank-shaft repaired by welding."**

IIS/IIW-73-61 (ex doc. X-229-59) (Commission X "Residual Stresses and Stress Relieving"): **"Observations on the results of torsion relaxation tests carried out on four typical heat-resisting steels"** by Dr. P. Brozzo (Italy)

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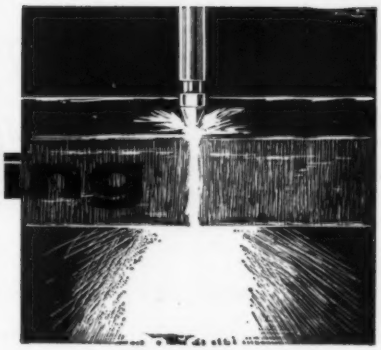

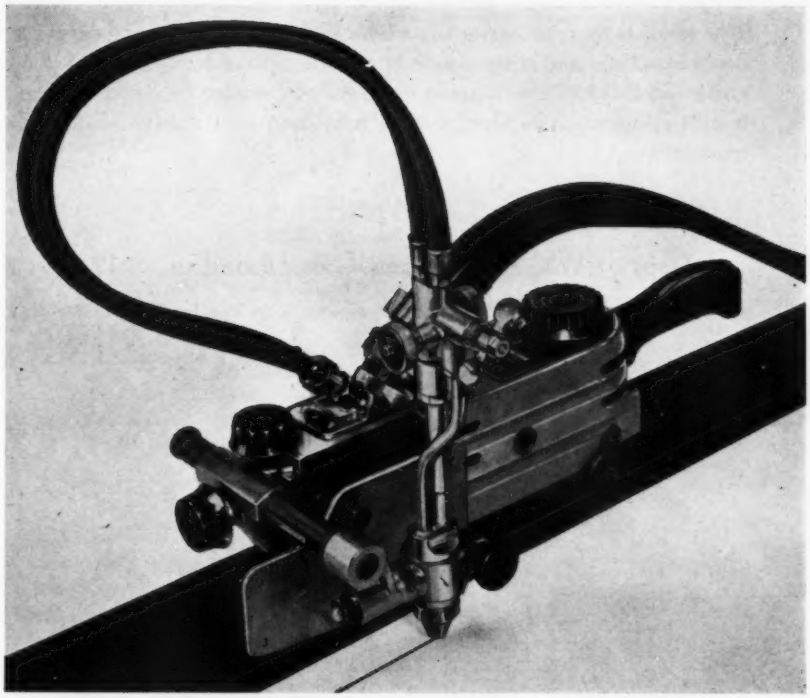

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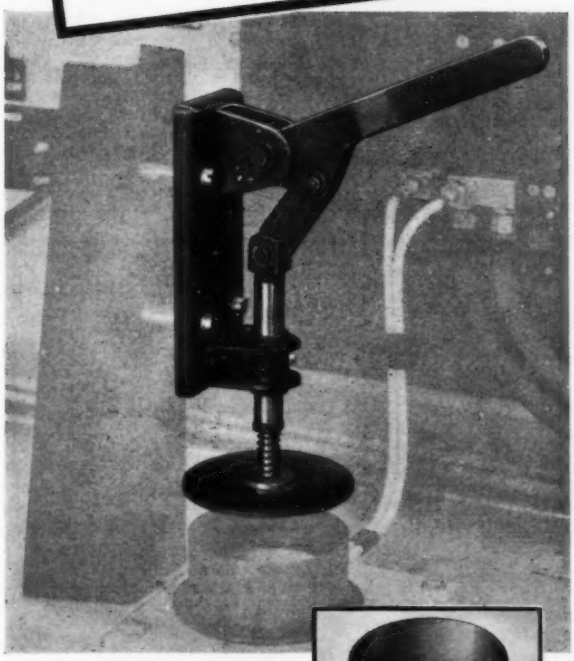

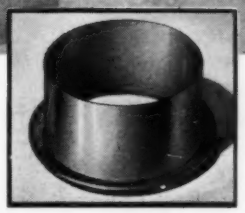

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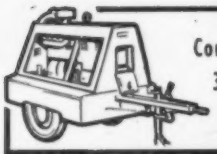

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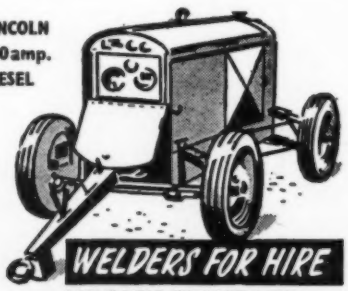

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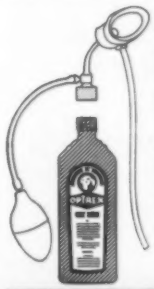

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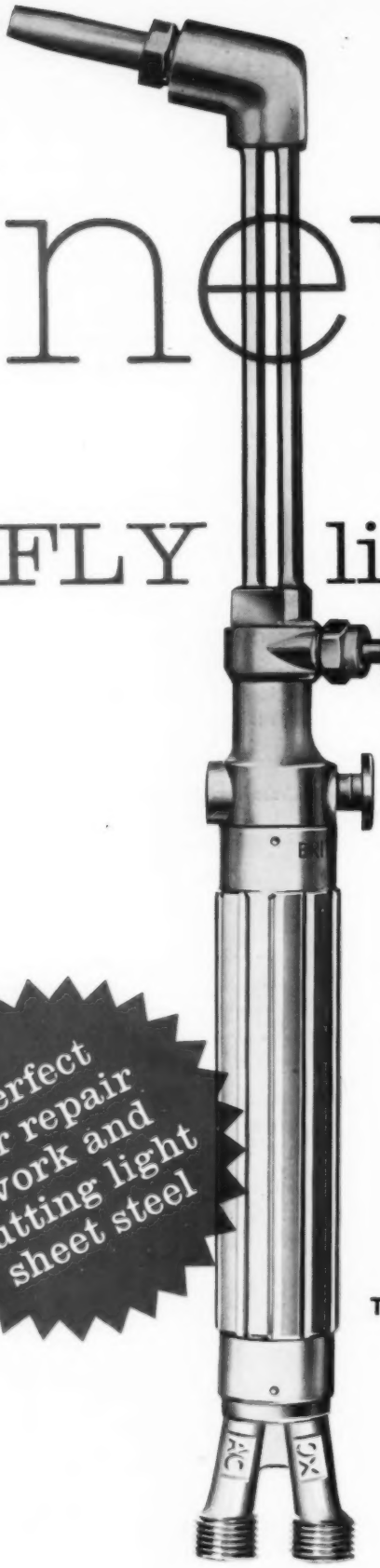

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